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A PRELIMINARY STUDY ON WIRE SAWING AND ITS COMPARISON WITH THE TRADITIONAL DRILL AND BLAST METHOD

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ABSTRACT

A Preliminary Study on Wire Sawing and its Comparison with the Traditional Drill and Blast Method

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The traditional drill and blast method has been the most common excavation method for excavating underground spaces. It is an effective method in terms of costs and productivity. However, in certain situations, blasting cannot always be used. For example, excavation close to a sensitive area where blasting may cause vibrations must be restricted. Wire saw cutting used together with the drilling and blasting method is an alternative.

As wire saw cutting is a relatively new technique for tunnelling, this thesis aims to provide a comprehensive literature review on this method based on previous studies. The purpose of the thesis is to present detailed information and data on the effectiveness and productivity of the wire saw cutting method, the mechanism of saw cutting, the forces of saw cutting and other important parameters related to the use of wire saw cutting. In addition, the theory of blasting vibrations and the effect of pre-cut discontinuity made by wire saw cutting on vibration reduction are discussed. The research also included a site visit and where wire saw cutting together with drilling and blasting were used in tunnel excavation.

This study offers extensive knowledge on wire saw cutting and its current state. Based on the literature review and the site visit, the most common advantages and problems of the method are presented. This knowledge can be used in future research to improve the use of wire saw cutting.

Keywords: Wire saw cutting, Tunnelling, Drill and Blast, Vibrations

TIIVISTELMÄ

Alustava tutkielma vaijerisahauksesta sekä menetelmän vertailu perinteiseen poraus- ja panostusmenetelmään

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Perinteisimmin maanalainen louhinta suoritetaan käyttämällä poraus- ja panostusmenetelmää. Menetelmä on tehokas sekä kustannusten että aikataulun osalta. Tietyissä tilanteissa kyseistä louhintamenetelmää ei kuitenkaan pystytä käyttämään perinteiseen tapaan. Tällainen tilanne voi olla esimerkiksi louhinta alueella, jossa räjähdyksen aiheuttamia tärinöitä täytyy rajoittaa lähellä sijaitsevien tärinäherkkien laitteiden tai rakennusten vuoksi. Vaijerisahaus käytettynä yhdessä poraus- ja panostusmenetelmän kanssa on yksi vaihtoehto tärinöiden rajoittamiseksi.

Vaijerisahauksen käyttö tunnelikohteissa on suhteellisen uusi louhintamenetelmä. Tästä syystä tämän tutkielman tarkoituksena on tuottaa kattava kirjallisuuskatsaus menetelmän käytöstä. Työssä esitetään tietoa menetelmän tehokkuudesta ja tuottavuudesta, leikkausmekanismiin sekä leikkausvoimiin liittyvää teoriatietoa sekä muuta tärkeää informaatiota menetelmään ja sen käyttöön liittyen. Tämän lisäksi työssä käsitellään räjäytystärinöitä sekä niiden etenemistä kallioperässä. Tämän pohjalta pohditaan vaijerisahauksella leikatun uran vaikutusta räjäytystärinöiden etenemiseen. Työn aikana suoritettiin myös vierailu tunnelityömaalle Ruotsiin, jossa vaijerisahausta käytettiin poraus- ja panostusmenetelmän apuna räjäytystärinöiden vähentämiseksi.

Työn tavoitteena on tarjota laaja katsaus vaijerisahaukseen ja sen nykyiseen tilaan kalliorakentamisen kohteissa kirjallisuuden ja työmaavierailun pohjalta. Tulevissa tutkimuksissa tätä tietoa voidaan hyödyntää kyseisen louhintamenetelmän kehittämiseen.

Asiasanat: Vaijerisahaus, Tunnelin louhinta, Poraus- ja panostusmenetelmä, Louhintatärinä

FOREWORD

This thesis was carried out from January 2021 to June 2021. I am very grateful to YIT Finland Ltd for offering and funding this interesting research project on wire saw cutting.

I would like to thank my supervisor at the university, Professor Zongxian Zhang. Thanks also go to my supervisors at YIT, Simo Laitinen, M.Sc., and Janne Isomäki, B.Eng., for guiding me and giving me the important knowledge and support I needed. I would also like to thank Kari Korhonen, M.Sc., for reading and commenting on my thesis and Markku Pyykkönen, B.Eng., for the interview in Krångede, Sweden.

Oulu, 29 June 2021

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LIST OF ABBREVIATIONS

A	amplitude
a	acceleration
CO	carbon monoxide
C_p	theoretical torque imposed on the wire
C_{ws}	compressional wave speed
D&B method	drill and blast method
FISE	qualification of professional in building sector in Finland
F_c	centrifugal force
F_k	structural coefficient
F_n	normal cutting force
F_p	force acting out of the cutting plane
F_t	tangential cutting force
f	frequency
K	constant representing material removing
k	transmission factor
k_p	stiffness of discontinuity
LHD	load, haul, dump machine
l	distance between the two rods used in blind-cut technique
m	mass of single diamond bead
M	moment acting on bead
N	newton
N_{OX}	nitrogen oxide
P_t	specific cut pressure on a unit length of the wire
PPV	peak particle velocity
p(x)	cutting pressure
Q_m	instantaneously detonating charge
RPM	revolutions per minute
R	radius of the cut
R_d	distance from blasting
R_p	reflection coefficient
T	wire tension
T_i	minimum wire tension

T_{i+1}	maximum wire tension
T_p	transmission coefficient
v_p	particle velocity
v_v	vibration velocity
v_f	feed speed
v_w	wire speed
v_1	peak particle velocity
w	width of cut
y	depth of cut
Z_p	seismic impedance
α_0	angular distance between two beads
$d\alpha$	infinitesimal arc portion that the single bead is bending during cutting
μ	friction coefficient
ρ_r	rock density
ω	circular frequency of incident blasting wave

1 INTRODUCTION

In underground construction, the traditional drill and blast method (the D&B method) has been the most commonly used method due to its time and cost effectiveness. However, underground excavations are increasingly being built close to already existing excavations or in an urban environment where buildings and different structures exist. One problem with the D&B method in these environments is the ground vibration and noise impact caused by blasting. At worst, vibrations caused by blasting can damage nearby existing excavations or buildings. To overcome these problems, a controlled blasting method can be used; however, there may be situations when even that is not enough to reduce the vibrations to the permitted level. In these situations, wire saw cutting used together with the D&B method is a possible alternative for performing the excavation work.

Wire saw cutting has been widely used for stone cutting in the dimension stone industry in recent decades, and also for removing large structures such as buildings, bridges, old concrete chimneys and dams (Huang & Xu 2013). The method has been effective and practical due to its flexibility, high production rate, low noise level, low cost and high energy efficiency, especially when compared to circular saws (Huang & Xu 2013). Moreover, a high degree of accuracy and a smooth cutting surface are also important benefits. Despite the widespread use of wire saw cutting in other fields of industry, it was not until quite recently that the method was studied by Gustafsson (2010) as a possible complement to the D&B method in vibration sensitive environments. The method was found to be a feasible alternative for tunnelling with high vibration regulations, although about twice as expensive as the D&B method. For tunnelling with less stringent vibration regulations it was found to be even more than double the cost. It was also found that a significant amount of time is needed to perform the cutting. Since then, several research projects investigating wire saw cutting performance and the effect of vibration reduction have been conducted, of which the most recent is Ahn (2020), which investigated cutting performance and improvement methods. It was also pointed out that there is not a fundamental understanding of wire saw rock cutting because neither the physical experiment nor the numerical analysis is straightforward (Ahn 2020).

In tunnel excavation, wire saw cutting is performed by using the so-called blind-cut technique. The blind-cut technique requires a number of guide holes to be drilled at the tunnel face before cutting. These guide holes are then used to insert two rods inside the drilled holes to allow the installation of wire to pass through the guide pulleys at the end of the rod. The wire is then connected to the rotary machine and, with the backward movement of the machine, the spinning wire is pushed against the rock mass. The desired shape of the tunnel determines the number of blind-cut holes that are drilled before cutting. The wire saw cuts can be done according to the situation on each surface of the tunnel (floor, walls, roof) or only partially by using the method (as shown in Figure 4).

The efficiency of wire saw cutting used together with the D&B method to control blast-induced vibrations is based on a slot made around the tunnel contour. Such an empty space between a blast source and a region where vibrations must be controlled will markedly reduce vibrations, as the slot will effectively stop or at least significantly reduce stress waves propagating from a blasting source (Zhang 2016).

In this thesis wire saw cutting is studied both theoretically and practically. The theoretical part is based on the existing literature, whereas the practical part is a case study of the hydropower plant in Krångede, Sweden, where YIT Sverige AB is building a 600-metre long access tunnel. The tunnelling is being executed by the combination of wire saw cutting and the D&B method. On the basis of the site visit and an interview conducted there, the advantages and disadvantages of the method are studied and presented.

This thesis is limited to studying the theory and mechanism of wire saw cutting as well as the theory of blast wave propagation through pre-cut discontinuity. The latter is an important topic related to the subject as the main advantage achieved by the combination of wire saw cutting and the D&B method is the reduction in vibration levels. Wire saw cutting is presented in cases where it is used for cutting shafts, cuts and tunnels. The ultimate aim of the thesis is to present a widespread review of wire saw cutting, its advantages and possibilities. This will provide knowledge specifically for the company that commissioned this research and for the industry in general, as well as other parties interested in the topic. This knowledge can be used to conduct further research in the field in the future.

2 THE D&B METHOD

Throughout history all around the world, tunnels have been built by people for various purposes, most typically as shelters, subway tunnels, highway tunnels, water tunnels, access tunnels, and tunnels for the mining industry. Due to its cost and time effectiveness, the traditional D&B method has been found to be one of most practical methods in various cases for medium to hard rock conditions. The D&B method can be used to excavate various shapes and sizes in an underground environment. In the urban environment, blast vibrations and noise are the most significant factors restricting the use of the method. When selecting a suitable excavation method, the following factors should be considered (Heiniö & Vanhatalo 1999):

- tunnel dimensions,
- tunnel geometry,
- length of tunnel,
- geological and rock mechanical conditions,
- ground water level and expected water inflow,
- vibration restrictions,
- allowed ground settlements, and
- worksite area limitations.

The process of the D&B method consists of the following phases (Heiniö & Vanhatalo 1999):

- pregrouting (in certain geological circumstances, either systematically or by probe analysis),
- drilling,
- charging,
- blasting,
- ventilation,
- loading and hauling,
- scaling, and

- rock reinforcement.

Due to the cyclical nature of the method, good site organisation is required.

2.1 Pregrouting

The purpose of pregrouting can be either to reduce water flow into the tunnel or strengthen possible fractures. If pregrouting is needed, it is done before the actual excavation work can begin/continue. In order to determine the need for it, probe holes are drilled to map fractures and water flow. Another option is to do pregrouting systematically as the tunnel progresses. To perform grouting, grout holes are drilled into the rock mass in a conical-fan shape at the tunnel face, typically at a length of 15–25 metres. The grouting agent is then pumped into the hole. Once the grouting agent has settled, tunnel excavation can begin. Depending on the grouting fan length and on the round length of excavation, grouting is executed every second, third, or fourth round (Heiniö & Vanhatalo 1999). Pregrouting is also beneficial for the guide holes of wire saw cutting if the rock mass quality is poor. This will make wire saw cutting easier as the fracturing of guide holes can be prevented.

2.2 Drilling

Drilling is carried out to drill holes for charging explosives, and it can be applied to a wide range of rock conditions, with diverse equipment. Equipment for drilling ranges from small handheld rock drills to large drill rigs (drilling jumbos) with even four drilling booms covering cross sections of up to 206 m^2 (Epiroc Finland Oy Ab b 2021).

Successful tunnelling requires that quality, safety and economy are considered. These aims are achieved with a proper drill and blast plan, which can hugely influence the productivity and total cost of tunnelling. According to Zhang (2016), successful tunnelling requires that all blastholes are fired and the rock is well fragmented, the tunnelling speed is as fast as possible, the fractured zone surrounding roofs and walls is as small as possible and tunnelling costs per metre are as low as possible.

When tunnelling, drill holes are typically divided into five groups: cut holes, slashing holes, roof holes, wall holes and floor holes (Zhang 2016). Usually, wall holes and roof holes are classified in the same group as contour holes. The purpose of these groups is to ensure successful and efficient tunnelling with good rock fragmentation, with the smallest excavation damaged zone (EDZ) as possible. To achieve these goals, all or at least some of the following factors should be considered in a proper drill and blast plan: tunnel dimensions, tunnel geometry, hole size, final quality requirements, geological and rock mechanical conditions, explosives and blast parameters, expected water leaks, vibration restrictions and drilling equipment (Heiniö & Vanhatalo 1999).

2.3 Charging and blasting

Drill holes are charged with an explosive suitable to the conditions. Explosives can be divided into two sub-categories: cartridges and bulk. When excavating in demanding environmental conditions and/or in population centres in Finland, only cartridges or emulsion-type explosives are accepted. Anfo-type explosives can still be used in some specific circumstances. Some factors to be considered when choosing a suitable explosive are, for example, the technical and environmental properties of the explosive, safety factors, water resistance, rock mass properties and storage properties/regulations.

Blasting should be carried out using a proper initiation sequence and delay time. A common initiation sequence is the following: cut holes, slashing holes, bottom holes and contour holes (Zhang 2016). The importance of a delay time between the ignitions of different blastholes is to provide a free surface and a swelling space for the blastholes. If these two factors are not met properly, the blasting result will not be good. With a proper design in drilling and blasting, the quality and stability of the tunnel will be good. A smooth and stable tunnel surface will also save costs in the subsequent phases of the tunnel excavation process.

2.4 Ventilation

After blasting ventilation is needed to remove toxic gas and dust. The concentration and components of the toxic gas depend on the type of explosive used; however, carbon monoxide (CO) and nitrogen oxide (NO_X) are the most common (Heiniö & Vanhatalo 1999). To ensure safe working conditions and keep production running without long interruptions, effective ventilation is needed.

2.5 Loading, hauling and scaling

After the toxic gas and dust are ventilated, blasted rocks must be loaded onto haul trucks/dumpers and transported to a surface level or crusher. Usually, loading is carried out with an LHD or wheel-loader.

Scaling is done to remove loose rocks from the tunnel surfaces (walls and roof). This is an essential part of safe underground excavation. It can be done both manually and mechanically, but mechanical scaling is the preferred method today. It improves the quality of scaling and the level of safety, productivity and effectiveness. Mechanical scaling in hard rock conditions is done with a hydraulic impact hammer with high-pressurised water mist/spray.

2.6 Rock reinforcement

Two fundamental methods of stabilisation in rock excavation are rock reinforcement and rock support. These stabilisation methods are used to prevent displacement, rockfalls and fluid flowing into the excavation. In rock reinforcement (e.g. bars, rods, cables, sprayed concrete), the aim is to reinforce discontinuum rock mass so that it begins to behave like a continuum. In rock supporting, direct structural support elements (e.g. steel arches or concrete rings) are installed in order to maintain displacement at tolerable levels (Hudson & Harrison 1997).

3 WIRE SAW CUTTING

Wire saw rock cutting has been widely practised in the dimension stone industry for decades, but it has been used in civil engineering projects since the 2010s. In tunnelling, this method can be used together with the traditional D&B method to perform controlled blasting. The greatest benefits provided by the combination of wire saw cutting and the D&B method are the reduction of ground vibration and noise, which is necessary in some sensitive areas. Wire saw cutting also provides possibilities to excavate precise geometrical dimensions into the rock mass. Moreover, the pre-cut surface after wire saw cutting is very smooth and the excavation damaged zone is minimal as blasting does not break the surrounding rock mass so much. This can be beneficial in certain situations. Moreover, a smooth excavation surface reduces the need for rock reinforcement. In particular, the volume of consumed shotcrete is reduced as the rock surface is smooth. Figure 1 presents the diamond wire that is used for wire saw cutting (Kabir et al. 2015).

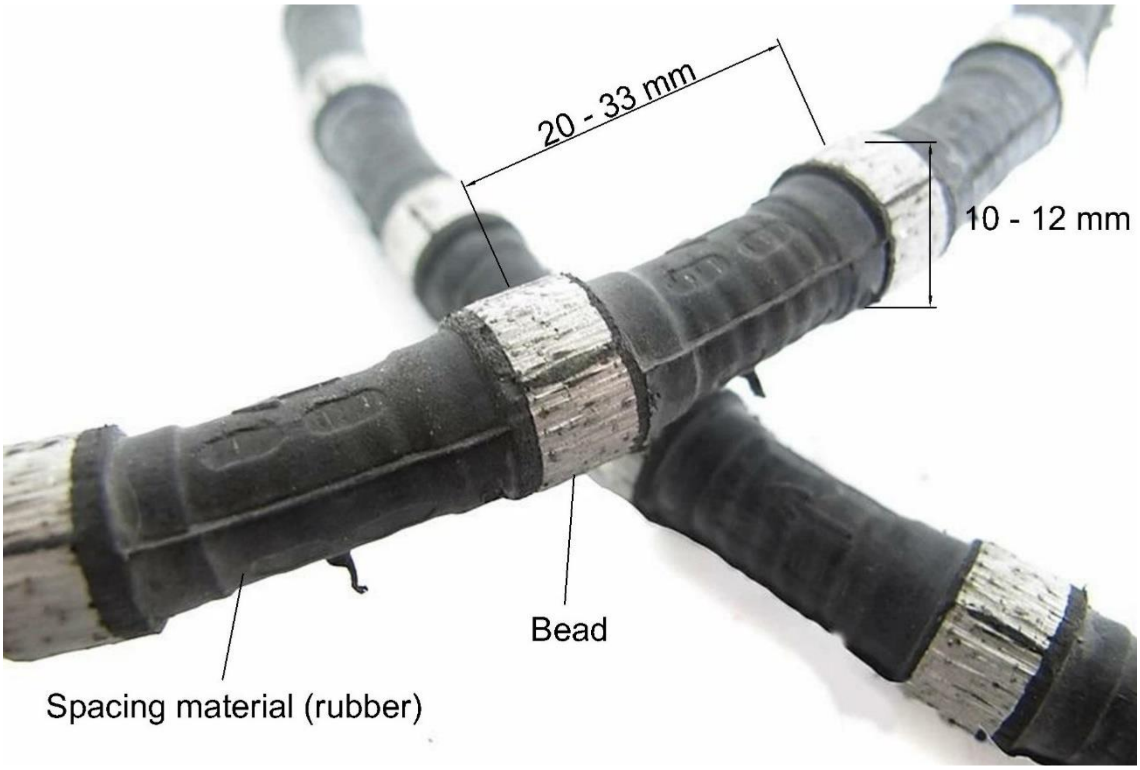

Figure 1. A diamond wire used for wire saw cutting. The wire consists of regularly spaced beads coated with diamond grains and the spacing material between the beads. The typical wire dimensions are presented in the figure (modified from Bau-Met Oy 2021).

When performing controlled blasting, the main purpose of using wire saw cutting together with the D&B method in tunnelling is to enclose the excavation circumference with a pre-cut slot (Lee et al. 2016). The slot around the blast source significantly reduces vibrations as the propagation of stress waves caused by blasting is restricted (Zhang 2016). When using this vibration-reduced excavation method, tunnelling or any underground excavation can be performed close to already existing buildings, structures or other underground excavations without causing disturbances or damage. The problem with most vibration reduction methods is that they need to be done at the expense of the time schedule and costs, which reduces the practicality and cost-efficiency of the work significantly (Lee et al. 2016; Zhang 2016).

Wire saw cutting as a method of vibration reduction in tunnelling was first studied by Gustafsson (2010). In Gustafsson's study, the use and economics of the method were studied and compared to the drill and blast method. In addition, the effects of tunnel profiles on stress distribution and rock reinforcement applications were also investigated. The results indicated that the method was applicable in vibration reduction but with approximately double the costs and a significant amount of time needed in wire saw cutting. Following that, investigations were undertaken to reduce the cutting time and improve cutting performance. Lee et al. (2016) studied wire saw cutting so that only the perimeter around the centre blast area is cut in order to reduce cutting time. The method was demonstrated to be effective in vibration reduction in a full-scale tunnel experiment. After that, the first wire saw cutting model was developed in 2017 by Lee et al. However, Ahn (2020) pointed out that a study providing a fundamental understanding of wire saw rock cutting was still lacking.

3.1 Applications of wire saw cutting

In this study, wire saw cutting is presented in cases where it is used for shafts, cuts and tunnels. In theory, the cutting mechanism itself is the same in all cases.

3.1.1 Shafts

A shaft is a vertical or diagonal excavation that has two access points from different levels. To cut a shaft with a wire saw, four holes in a square or rectangular pattern are drilled down from the surface level to allow the installation of the wire. The holes are typically angled out from each other in order to ensure that the rock volume does not get stuck after cutting. The wire is fed down through one hole and then back up to the surface through another hole. The wire ends are then connected and installed to drive the pulley of the wire saw machine. The machine is installed on rails and can be placed on the surface or in the tunnel. The wire positioned around the rock is then pulled by the backward movement of the machine on rails to cut the rock. The backward movement of the machine on rails produces tension in the wire, which provides the actual cutting mechanism. The principle of wire saw cutting in a shaft excavation is presented in Figure 2. When the cutting of the first side is completed, the wire is moved to another hole to start the cutting process again (Gustafsson 2010).

Under the wire sawn block, a concrete pillar must be cast to bear the weight of the rock mass once all four sides are cut. When the sawn block is no longer connected to the surrounding rock mass, it is blasted. Gravity allows the blasted rock mass to fall into the tunnel. From the tunnel level it can be loaded and hauled to the surface. The rock mass can also be lowered down through the shaft by using mould bars in the excavated area with the help of a hydraulic jack (Gustafsson 2010).

Wire saw cutting in shaft excavation is an effective method. It is a method with both low vibration and noise levels, producing a smooth wall as the end result. This reduces the amount of reinforcement needed and, in some cases, such as for ventilation purposes, a smooth surface is preferable as it reduces air resistance. Tolerance in the excavation accuracy of the method is also at a high level.

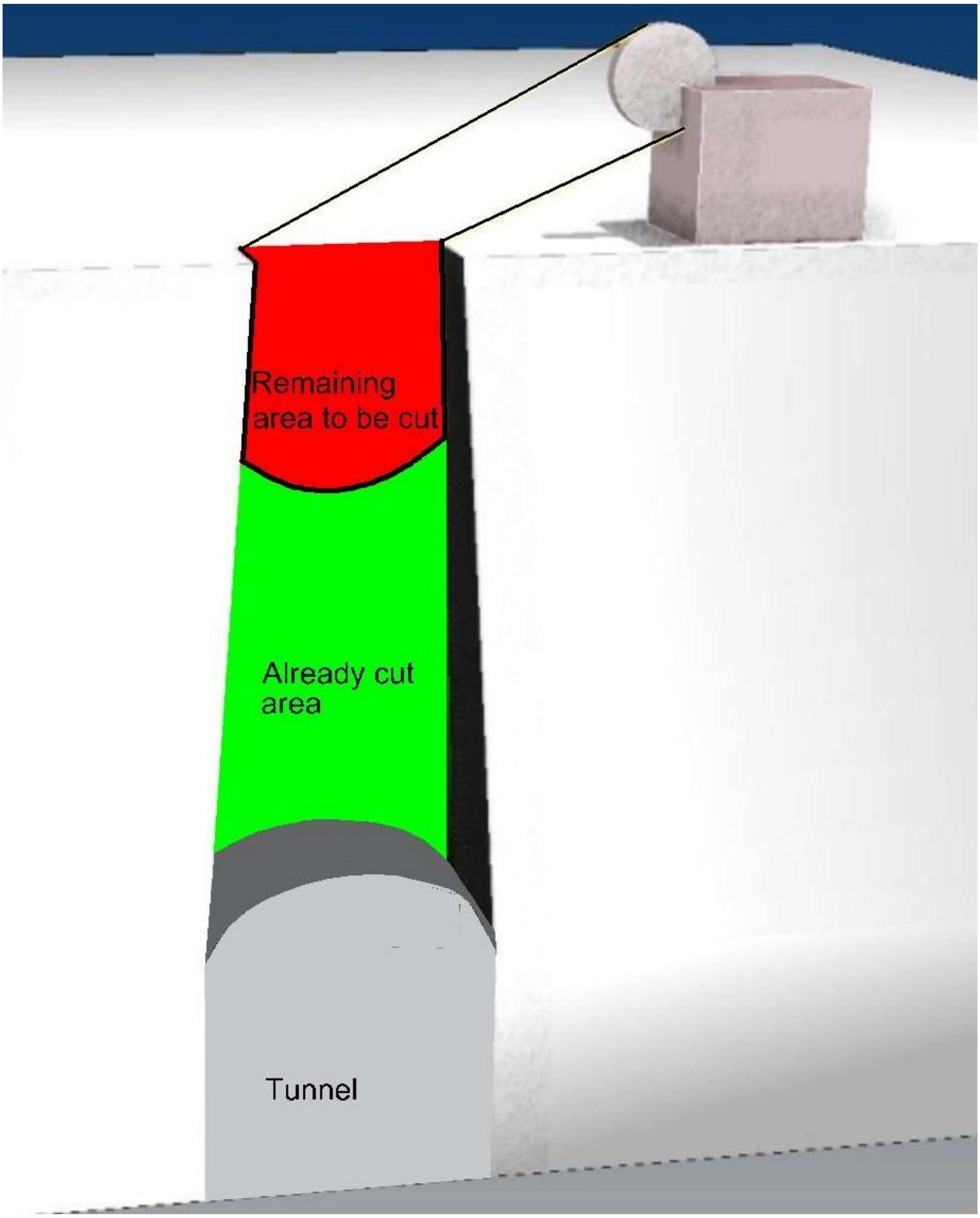

Figure 2. Principle of cutting a shaft with a wire saw (modified from Gustafsson 2010).

3.1.2 Cuts

To perform cuts with the wire saw cutting method, the procedure is slightly different from the one previously presented as the wire cannot be wrapped around the rock to be cut. The method required to perform cuts of this kind is the so-called blind-cut technique.

To perform the blind-cut technique, pre-drilled guide holes are drilled to the desired depth. These vertically drilled guide holes are used to insert two rods with a pulley at the end. The wire is fed down the hole and back up with the help of the pulley, and then the same route for the second hole. The wire ends are then connected, and the wire is connected to the drive pulley of the wire saw machine that runs on rails. The difference between this cutting operation and the one used for shafts is that the wire is pushed towards the cutting piece instead of pulling it back through it, as illustrated in Figure 3. For this reason, cutting efficiency is reduced by approximately 35–40% compared with pulling the wire (Gustafsson 2010).

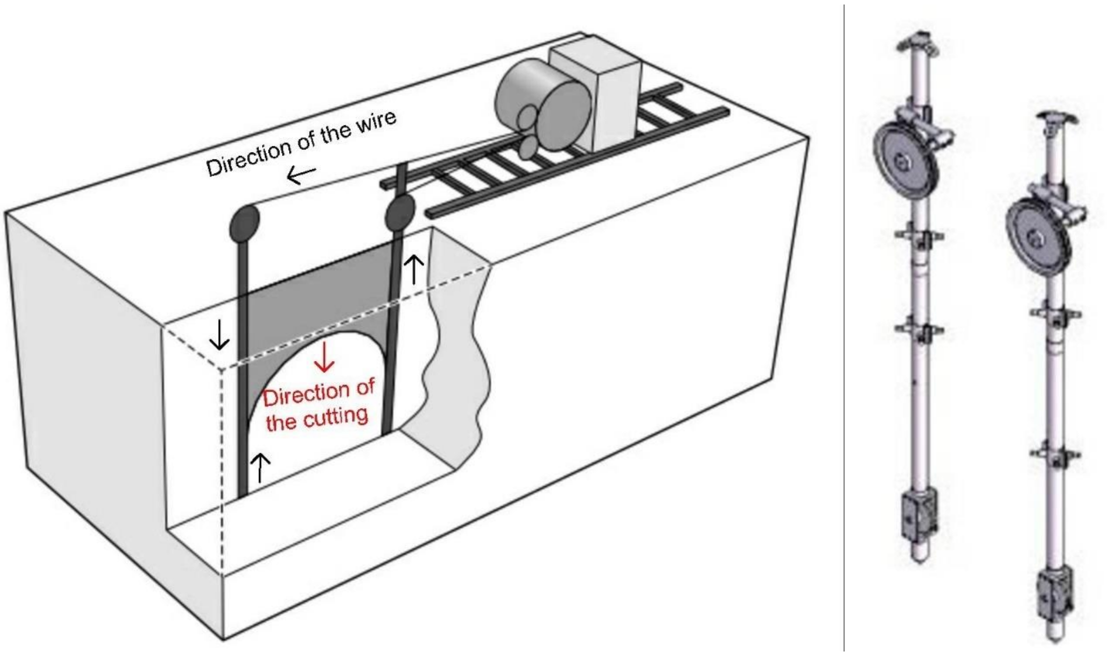

Figure 3. Blind-cut technique applied to perform a cut from the surface. The two rods presented on the right are used to perform the blind-cut technique (modified from Epiroc Finland Oy Ab a 2021).

In this method, as vertical holes are used, it is important to use a bilge pump placed at the bottom of the guide hole. Otherwise, the cooling water and cuttings would accumulate at the bottom of the drill hole, which would reduce the cutting efficiency. There could also be a risk that the water and cuttings could interfere with the wire and cause it to slide over the rock instead of cutting it (Gustafsson 2010).

After the cutting is done on all the sides of the block, the block is still connected at the bottom. According to vibration limits, the rock mass can be blasted with one or more rounds or then broken into pieces by a hydraulic impact hammer (Gustafsson 2010). Other methods for excavating the rock mass are, for example, a hydraulic rock splitter or expansive mortar/expansive demolition grout. Both methods require drill holes. A hydraulic splitter splits the rock mass by wedging it and expansive mortar is a mixture of elements that initiates when water is added to the dry mix. Due to the chemical reaction, the material expands aggressively in the drill holes. The expansive force causes the rock to break. Both previously mentioned excavation methods are non-explosive methods and therefore do not cause vibrations.

The diameter of the blind-cut holes can have a huge effect on the cutting operation. According to the literature, diameters ranging from 250 mm to 370 mm are typically used. With a smaller diameter, the drilling costs are lower as the work can be performed faster, but the problem is that the stress on the wire is high when the pulley diameter is small. This can cause damage to the wire and therefore early rope failure. The angular velocity of a small pulley is high, which can strain the pulley a lot. With larger pulleys these problems can be alleviated and the tension in the wire can be greater, thus making the cutting more effective. However, drilling costs with a larger diameter are much higher, so the most cost-effective option should be chosen according to these factors. These problems were already recognised and the effectiveness of wire saw cutting was to be developed (Ahn 2020; Gustafsson 2010).

3.1.3 Tunnels

For tunnelling, the technique used for wire saw cutting is the same as used for cuts, but the number of blind-cut holes depends on the desired tunnel shape. With a greater number of blind-cut holes it is possible to make more rounded tunnel shapes, which naturally results in more time used for drilling and wire sawing. This obviously leads to higher costs. Depending on the situation, it is also possible to cut just the bottom, walls and/or roof. Typically, the permitted vibration limits and schedule determine whether all the sides will be cut or not. If a slot is made around the whole tunnel circumference, vibrations can be limited more. As wire saw cutting is a time-consuming method compared to the traditional D&B method, it is typically used only in special situations (Gustafsson 2010). Such a situation could be, for example, when a tunnel crosses close to an already existing tunnel or close to an inhabited area and blasting is therefore restricted. Figure 4 shows a schematic view of wire saw cutting in tunnel excavation.

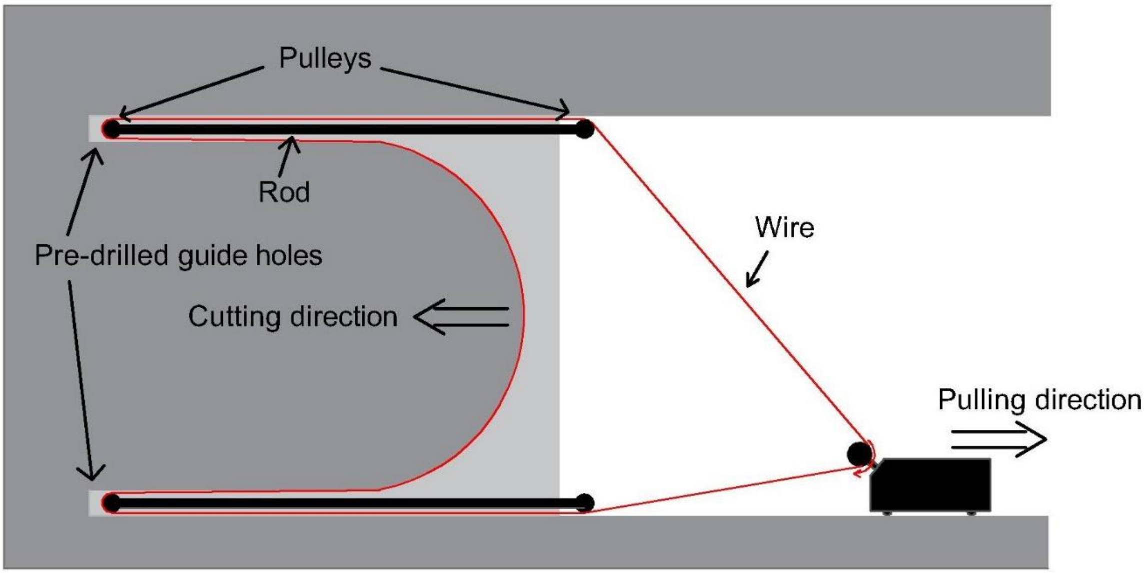

Figure 4. Schematic diagram of wire saw cutting in a tunnel profile (after Lee et al. 2017).

Implementation of wire saw cutting is much easier if the tunnel face is accessed from both ends (Gustafsson 2010). Holes can be drilled through the rock mass so the wire can be wrapped around the rock and connected to the rotary machine. The technique is thus similar to that used in shaft cutting. If wire saw cutting can be applied in this way, the cutting process is simpler and more effective.

After all the sides are cut (as shown in Figure 5), the rock mass is still attached at the back side. To cut the last side the rods need to be moved and the wire installed again, which is complicated and time-consuming, according to Gustafsson (2010). Another option is to drill and blast the remaining part of the rock mass. As the slot is cut around the tunnel circumference, seismic waves are partially prevented from travelling through the discontinuity. If the vibration limits are really tight, blasting can be implemented to blast a small round just once or use a hydraulic rock splitter or expansive mortar.

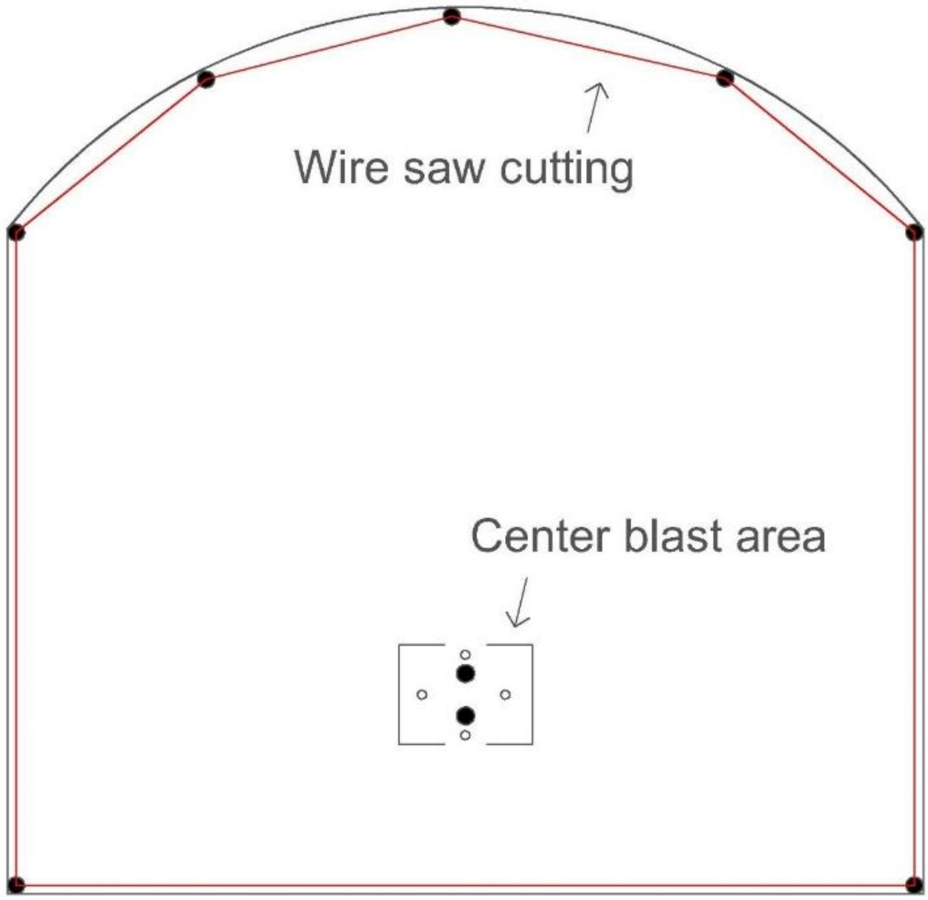

Figure 5. Wire saw cutting around the whole tunnel circumference (after Lee et al. 2017).

Lee et al. (2016) have also studied a method for performing wire saw cutting just around the centre blast area to produce a pre-cut discontinuity. The centre blast area means the cut holes in blasting, which are the holes that produce the largest vibration as the specific charge in those holes is the highest. Performing wire saw cutting this way means an enormous amount of time and costs can be saved as the area being cut would be much smaller. Figure 6 illustrates the use of pre-cut discontinuity around the centre blast area (Lee et al. 2016).

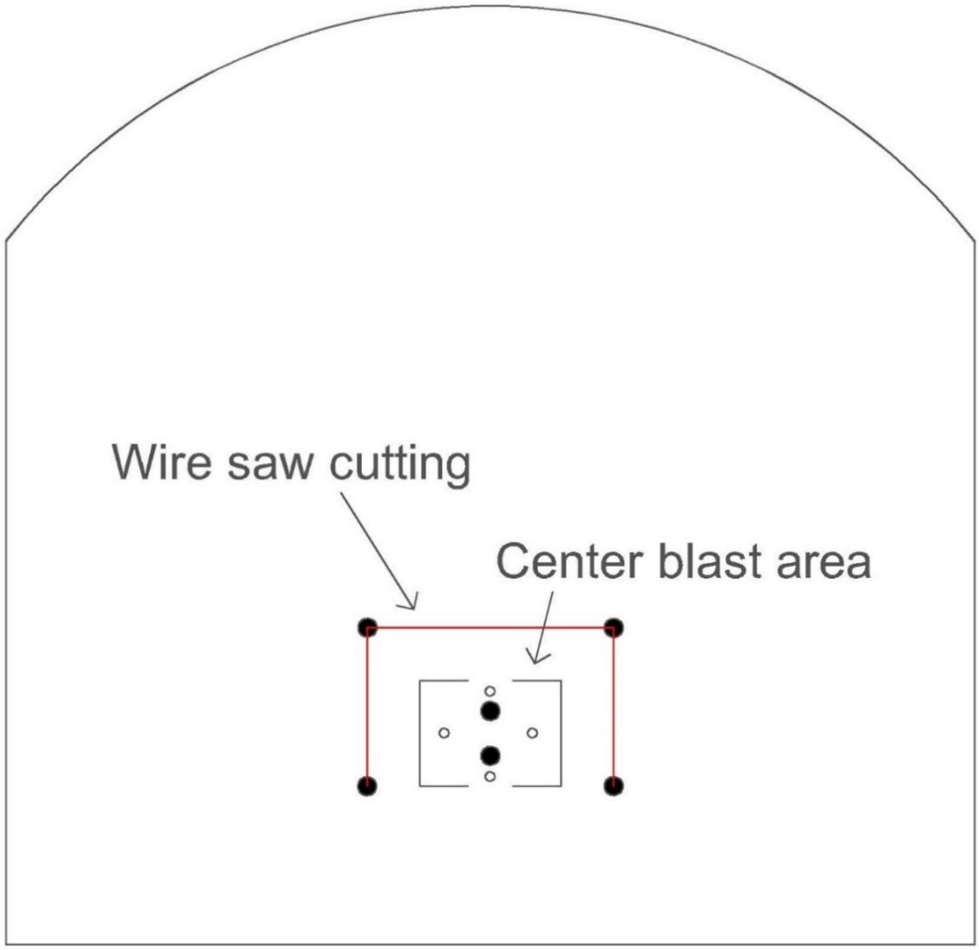

Figure 6. Wire saw cutting around centre blast area (after Lee et al. 2017).

According to calculations, Lee et al. (2016) predicted the peak particle velocity (PPV) to be reduced by 50% if compared before and after the pre-cut. PPV is a measure of ground vibration. However, the results from the experimental study were not that clear, partly because the pre-cut depth was not deep enough and partly because small amounts of charges were used near the area of concern. The results of the numerical analysis, proven using appropriate analytical solutions, showed that a significant reduction of PPV can be achieved if the ideal conditions are met in the field. Therefore, one significant way to reduce vibrations with efficient cutting in less time would be to use pre-cut discontinuity around the centre blast area (Lee et al. 2016).

4 PROCEDURE OF WIRE SAW CUTTING

4.1 Cutting process in general

Wire saw cutting involves a cutting wire that cut through the block, forming a continuous loop around the driving pulley of a wire saw machine and stone block as explained in Figures 2, 3 and 4. This continuous spinning wire loop is pulled or pushed through the block (Engin 2013). Through the combination of this pulling/pushing force and the spinning wire, the cutting action is provided (Engin 2013). The spinning action is provided by the spinning drive wheel of the wire saw machine, and the required tension and rotation force by the backward movement of the machine on the rail (Ghaysari et al. 2012). The cutting is thus an interactive process between the block and the wire (Ahn 2020). Even though the term 'sawing' is usually used to describe the cutting action, a more accurate term would be a grinding process (Tönshoff et al. 2002). In outline, the entire cutting operation depends on the wire speed, feed rate, sawing length, wire tension and flushing (Huang & Xu 2013). Thus, the cutting efficiency is hugely influenced by the power and characteristics of the wire saw machine.

4.2 Structure of the wire

The wire used for wire saw cutting is called a diamond wire. In general, a diamond wire is a steel cable that consists of regularly spaced beads coated with small diamond grains. The steel cable is flexible as it consists of several thin, concentrically wound steel wires (Ahn 2020). The beads coated with diamond grains offer the abrasive cutting action needed for the cutting procedure and are thus the most important part of the diamond wire (Engin 2013). For stone cutting, the number of beads per metre is commonly 30–48, with a diameter of 10–12 mm (Mactech 2021).

The diamond grains are bonded in beads by electroplating or impregnated metal power bonding. As the wear resistance of electroplated beads is lower, these are normally used for softer rock types, such as marble (Butler-Smith 1997). Impregnated metal power bonding like as used for sintered beads, are used for harder rock types, such as granite

(Butler-Smith 1997). Sintered beads are a composite of diamond grains and mixed metals which are heated and compressed to form a solid bead (Mactech 2021). The technology used for manufacturing sintered diamond beads is similar to that used for manufacturing diamond drill bits and diamond saw blades (Butler-Smith 1997). Commonly, the total volume of the active part of the bead is ~220 mm^3, of which 26% is the volume of diamond grains and 74% the volume of metallic matrix (Cardu & Michelotti 2008).

Between each bead is a spacing material covering the cable to protect it from abrasion and also fixing the beads in place. The spacing material thus eliminates any direct contact between the wire and the abrasive rock and between the bead and the wire (Butler-Smith 1997). Commonly, the material is rubber or plastic. Rubber is a better option as it is more flexible and it has a higher heat resistance (Mactech 2021).

There are few options for the bead shape: cylindrical, conical and bi-conical (Mactech 2021). Different bead shapes offer different cutting properties and are therefore suitable for different materials. A cylindrical shape and sintered beads is the most typical combination and is the one used for stone cutting usually. Diamond grains are lab-manufactured diamonds and the shape can range from jagged and sharp to angular and crystalline. A different shape and the size and quality of the diamond offer different cutting properties. The size of the diamond grains, which are sintered on the bead, is typically from 0.2–0.4 mm (Cardu & Michelotti 2008).

4.3 Factors affecting the effectiveness of wire saw cutting

Parameters affecting the cutting efficiency of the wire cutting method can be divided into non-controlled parameters and partially controlled parameters. Non-controlled parameters include rock properties and the second group includes cutting machine properties and operating conditions. The most important criteria in the wire saw cutting method to consider are electric energy consumption, cutting rate/production rate, cutting wire cost, cutting wire efficiency for lifetime, diamond bead wear rate and specific energy of cutting (Almasi et al. 2015). The parameters that affect cutting efficiency are shown in Table 1 (Ozcelik et al. 2004).

Table 1. Parameters that affect wire cutting efficiency (after Almasi et al. 2015; Ozcelik et al. 2004; Ozcelik & Yilmazkaya 2011).

Non-controlled parameters	**Partially controlled parameters**	
Rock characteristics	**Cutting characteristics**	**Operating conditions**
Physical properties Density Porosity Texture Particle size and shape Cementation type and degree Quartz content Water absorption coefficient Water content Wave's conductivity **Mechanical properties** Rock hardness Rock strength Abrasiveness Brittleness Elasticity **Structural properties** Discontinuities	**Machine properties** Machine power Voltage required by the machine Diameter of pulleys Structure and type of diamond bead Diamond grits size, type, and density **Operational properties** Wire speed Pull-back force/thrust force Geometry of wire during cutting Dimensions of block Cutting type Distance between machine and face Flushing efficiency	Technical personnel Used techniques Allowed working hours on the site Other restrictions and regulations related to the worksite

4.3.1 Rock characteristics

Under the group of non-controlled parameters, existing rock properties include the physical, mechanical and textural properties of rock. These parameters are defined by the rock mass and its geological origin and cannot therefore be influenced in any way. If those properties are well known beforehand, partially controlled parameters can be adjusted under the consideration of non-controlled parameters so that the cutting will be as efficient as possible, as the selection of the optimum machine and operation techniques in rock engineering is mostly dependent on the textural and mechanical properties of rock (Ozcelik et al. 2004). Figure 7 shows the effects of different rock properties on the cutting rate (Topal & Kuruppu 2010).

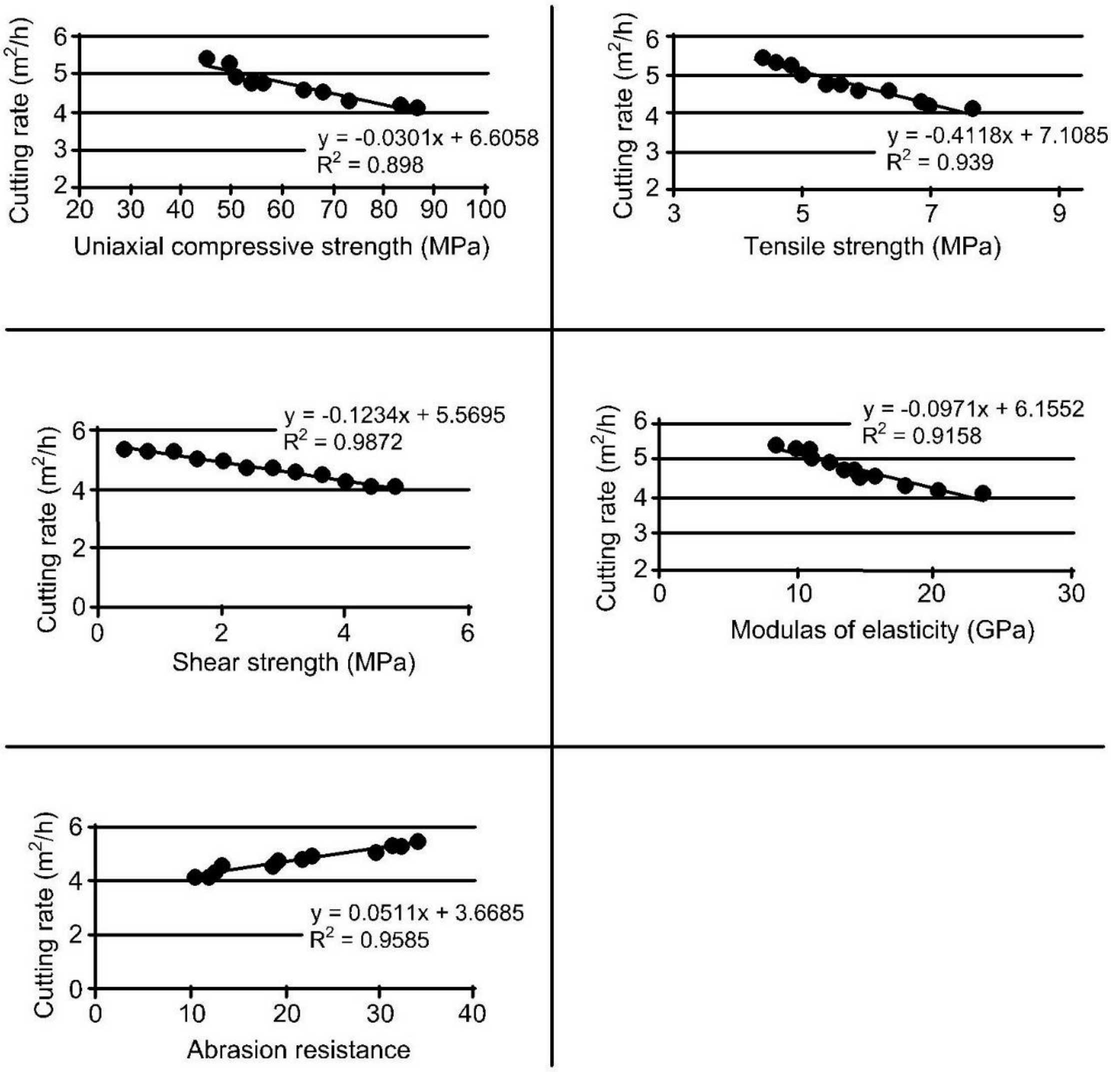

Figure 7. The effects of different physical and mechanical properties of rock on the cutting rate in wire saw cutting (after Topal & Kuruppu 2010).

4.3.2 Operating parameters

The cutting rate of the wire saw is determined as (Rajpurohit et al. 2020):

$$CR = A/t \tag{1}$$

where CR is the cutting rate of wire saw (m^2/h),
A is the surface area of the block to be cut (m^2), and
t is time taken to cut the area (h).

According to the study of Lee et al. (2017), the cutting rate in wire saw cutting used for tunnel excavation varies from 2 to 5 m^2/h. If compared to the cutting rate when the wire can be pulled through the stone instead of pushing, as in the blind-cut technique, these vary from 5 to 11 m^2/h, according to the literature (Almasi et al. 2015; Ghaysari et al. 2012; Rahimdel & Bagherpour 2018; Sadegheslam et al. 2013). Gustafsson (2010) states in his study that the cutting rate for the blind-cut technique is approximately 3540% lower than in pulling technique. On the basis of the above, the estimate that Gustafsson (2010) makes on the cutting rate difference between these two methods is valid.

Lee et al. (2017) used a mathematical simulation which was verified by a test machine on the laboratory scale. The equipment used in the test was similar to that used for the blind-cut technique in tunnelling. Figure 8 shows the results of their study. Based on the results, the cutting rate increase is identical under the influence of wire speed and tension. The higher the wire saw speed and the tension force, the better the cutting rate. However, if the feed speed is excessive, cutting performance decreases as the time to remove rock cuttings is not optimal. The effect of feed speed on the cutting rate can also be seen in Figure 8. The parameter values used for the simulation were the following (Lee et al. 2017):

- wire speed $v_w = 28$ m/s,
- wire tension $T_{out} = 5$ kN, and
- feed speed $v_f = 12.4 \times 10^{-4}$ m/s.

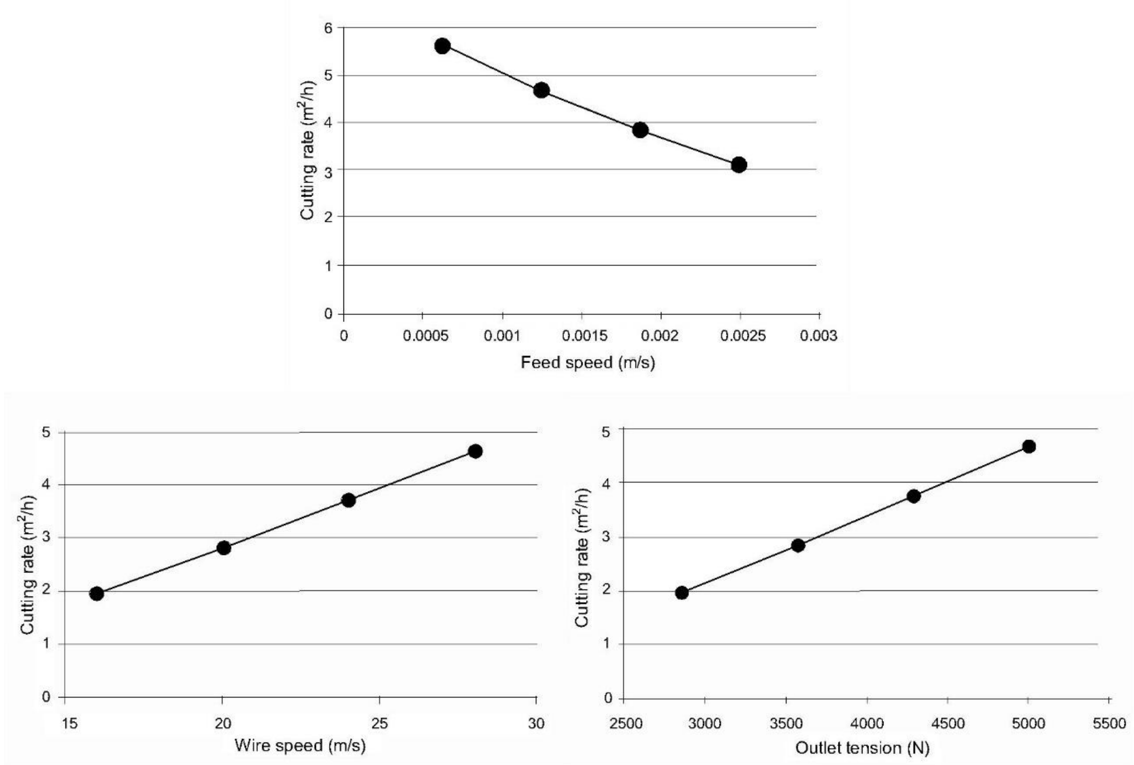

Figure 8. The influence of feed speed, wire speed and outlet tension of the wire on the cutting rate (after Lee et al. 2017).

As the effectiveness and performance of wire saw cutting is hugely influenced by wire speed and wire tension, it can be said that the cutting performance is directly dependent on machine power, as power is determined by the multiplication of RPM and torque (Lee et al. 2017). The power of a wire saw machine is thus the most significant factor to consider from the operating parameters in order to improve the cutting rate.

The cutting rate in wire saw cutting is also dependent on the cutting rate constant and friction. The cutting rate constant may vary according to the worksite conditions, so friction has a significant impact on the material removed by the wire saw. Therefore, with higher friction, more material can be removed. One way to influence the frictional coefficient is the flushing fluid used during the cutting process (Ahn 2020).

4.3.3 Setting parameters

The most significant setting parameters in the blind-cut technique affecting the cutting performance are the cutting width and distance between the pulleys at the ends of the two rods (as shown in Figure 9). The depth of the cutting does not influence the cutting rate, according to the results of Lee et al. (2017). As the cutting width increases, the cutting performance decreases because the radius of the wire saw bow shape becomes larger (as shown in Figure 9). As the radius of the wire saw bow shape increases, the area of the final cutting surface, which is possible to perform, decreases. To make the cutting width smaller, more holes are needed to cut the same amount of area; however, this also means higher costs. If the distance between the two rods is increased, wire saw bow shape becomes flatter (as shown in Figure 9), which results in an increase of the total cutting area. To increase the distance between the pulleys, larger diameter holes should be drilled, which causes a cost increase due to drilling more holes to reduce the cutting width. Therefore, when a parameter change is made in order to improve cutting performance, the cost should be carefully investigated. The influence of setting parameters on the cutting rate is shown in Figure 10 (Lee et al. 2017).

Setting parameters used for the simulation were in the following (Lee et al. 2017):

- depth of the cut y = 1.5 m,
- width of the cut w = 1 m, and
- distance between the two pulleys l = 1,345 m.

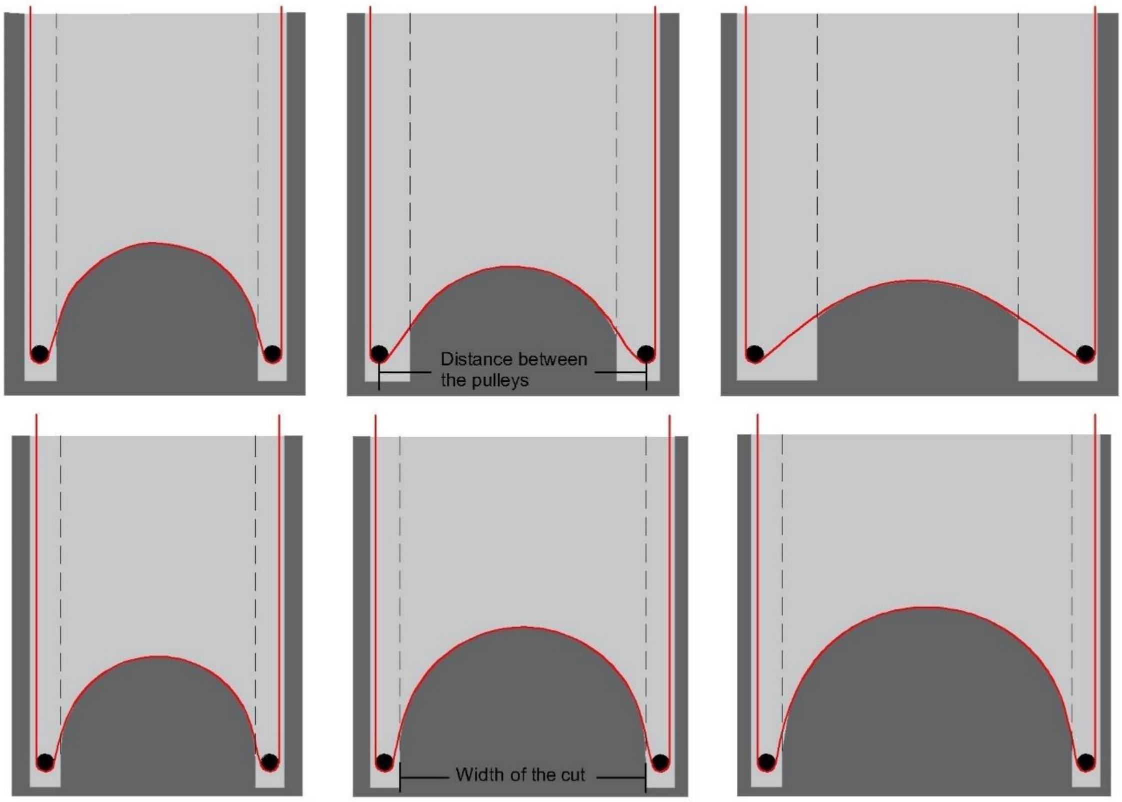

Figure 9. The most significant setting parameters of the cut: width of the cut and distance between the pulleys (after Lee et al. 2017).

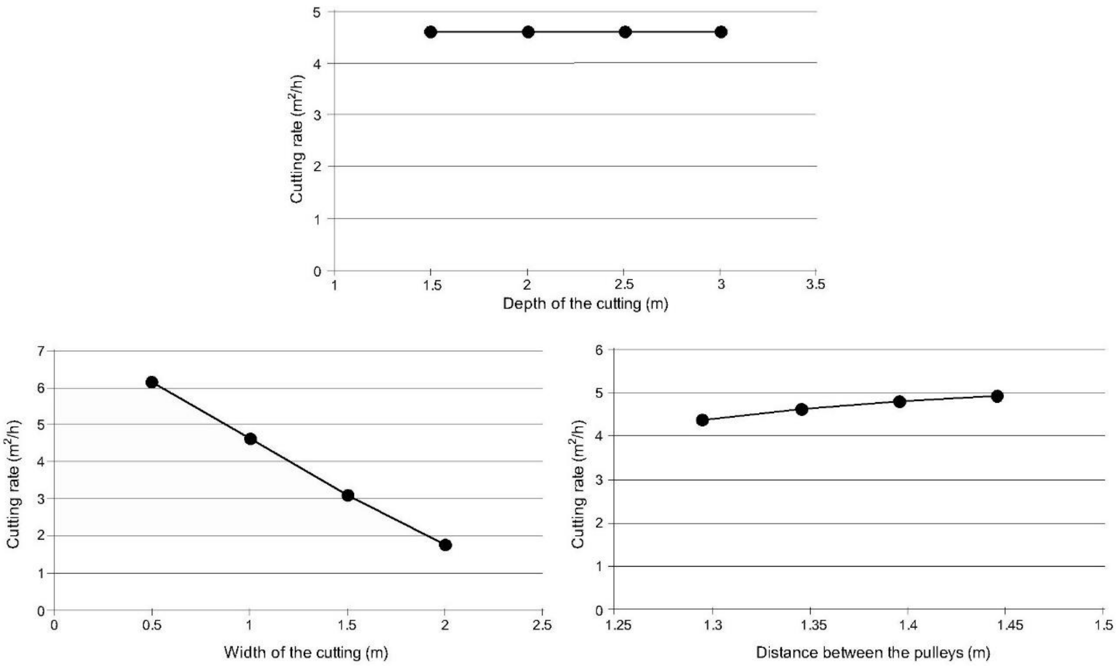

Figure 10. The influence of cutting depth, width and distance between the two pulleys on the cutting rate (after Lee et al. 2017).

4.3.4 Thrust force

Figure 11 shows the results of the study conducted by Almasi et al. (2015). In this research, different block sizes were cut with different thrust/pullback forces. Thrust force in wire saw cutting can be adjusted by the amperage level of the machine. The cutting dimensions varied from 10 x 5m to 10 x 10m. According to the results, a higher level of thrust force is recommended if the cutting surface is small. Alternatively, if the cutting surface is large, a low thrust force is more efficient in terms of the cutting rate. However, more detailed studies should be conducted in the case of tunnel excavation in order to verify the applicability of this theory for the blind-cut technique that is used for tunnelling.

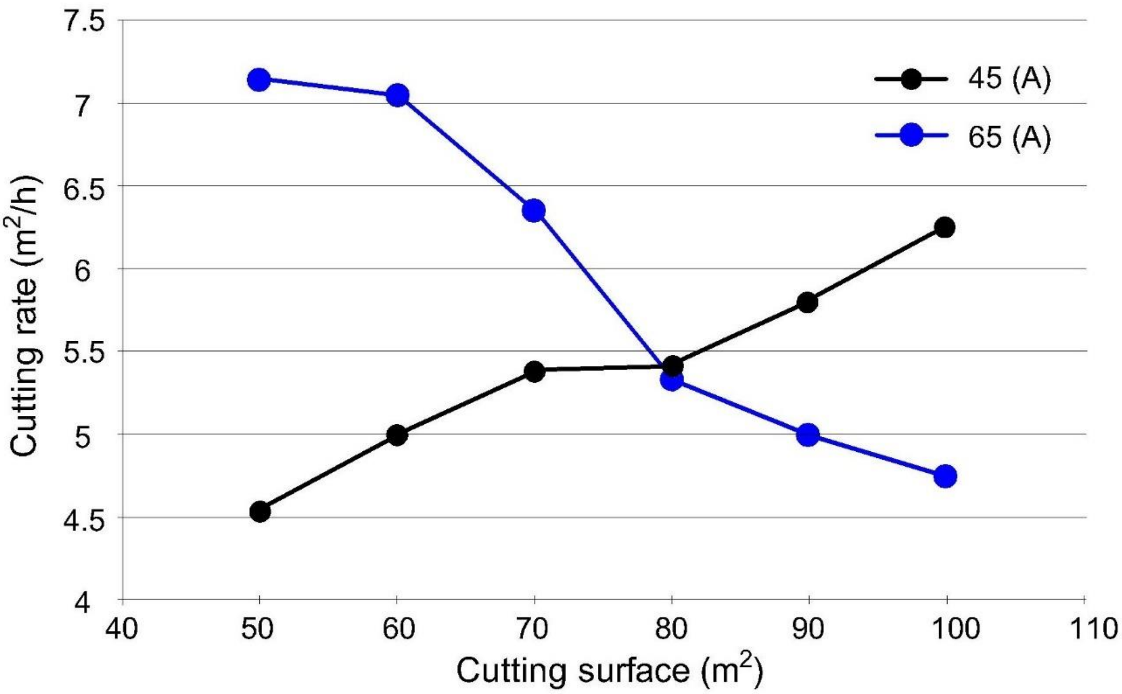

Figure 11. Cutting rate against cutting surface for thrust forces of 45 and 65 amperes (after Almasi et al. 2015).

4.3.5 Cutting performance vs cutting time

One significant issue pointed out in the Lee et al. (2017) study is that the cutting speed exponentially decreases as the cutting time elapses. According to results in that study, the majority of cutting was already complete within a relatively short time. The results showed that when only 57% of whole cutting time had elapsed, 90% of the total cutting area had been cut (as shown in Figure 12). This means that cutting performance dramatically decreases with time. Another issue pointed out was that the final cutting area was almost half of the expected area (0.85 m^2 compared to 1.5 m^2). The reason for the decreased cutting performance and cutting area is the excessive curved wire saw bow shape (as shown in Figure 9 and discussed in Paragraph 4.3.3). If the bow shape is high, cutting forces decrease, unless the wire tension increases in the same proportion. To keep the bow shape flatter, the distance between the two rods, which are installed in the holes, needs to be large enough. This can be achieved with a larger diameter of the pre-drilled holes, as discussed previously. As cutting performance decreases over time and the final area cut does not match expectations, it is important to determine a target cutting area and duration in order to perform the cut in an effective manner (Lee at al. 2017).

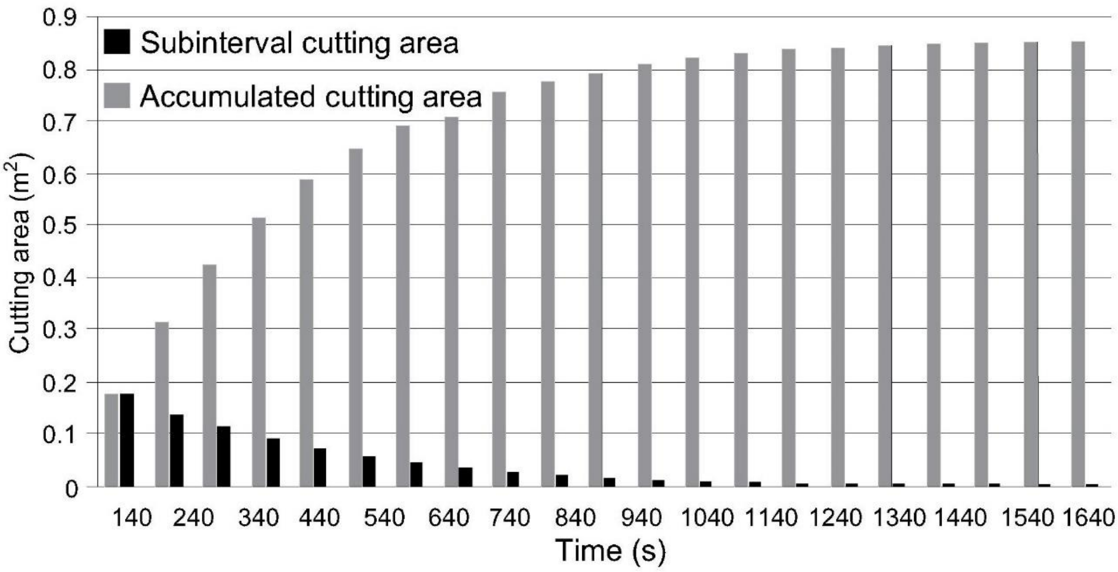

Figure 12. Accumulated and subinterval cutting area against time (after Lee et al. 2017).

4.4 Cutting forces and tensions

In the cutting process, the diamond grains in contact with the cutting surface produce grinding, cutting or abrading (Engin 2013). The type of cutting depends on the contact angle between the diamond grain and rock surface. This angle varies according to the path of the wire in the rock. The contact between the beads and the rock surface, as well as the forces acting on the beads during the cutting, is presented in Figure 13. Each of the diamond beads is pressed against the rock due to the inner tensions of the wire caused by the spinning wire and backward movement of the wire saw machine (Huang & Xu 2013).

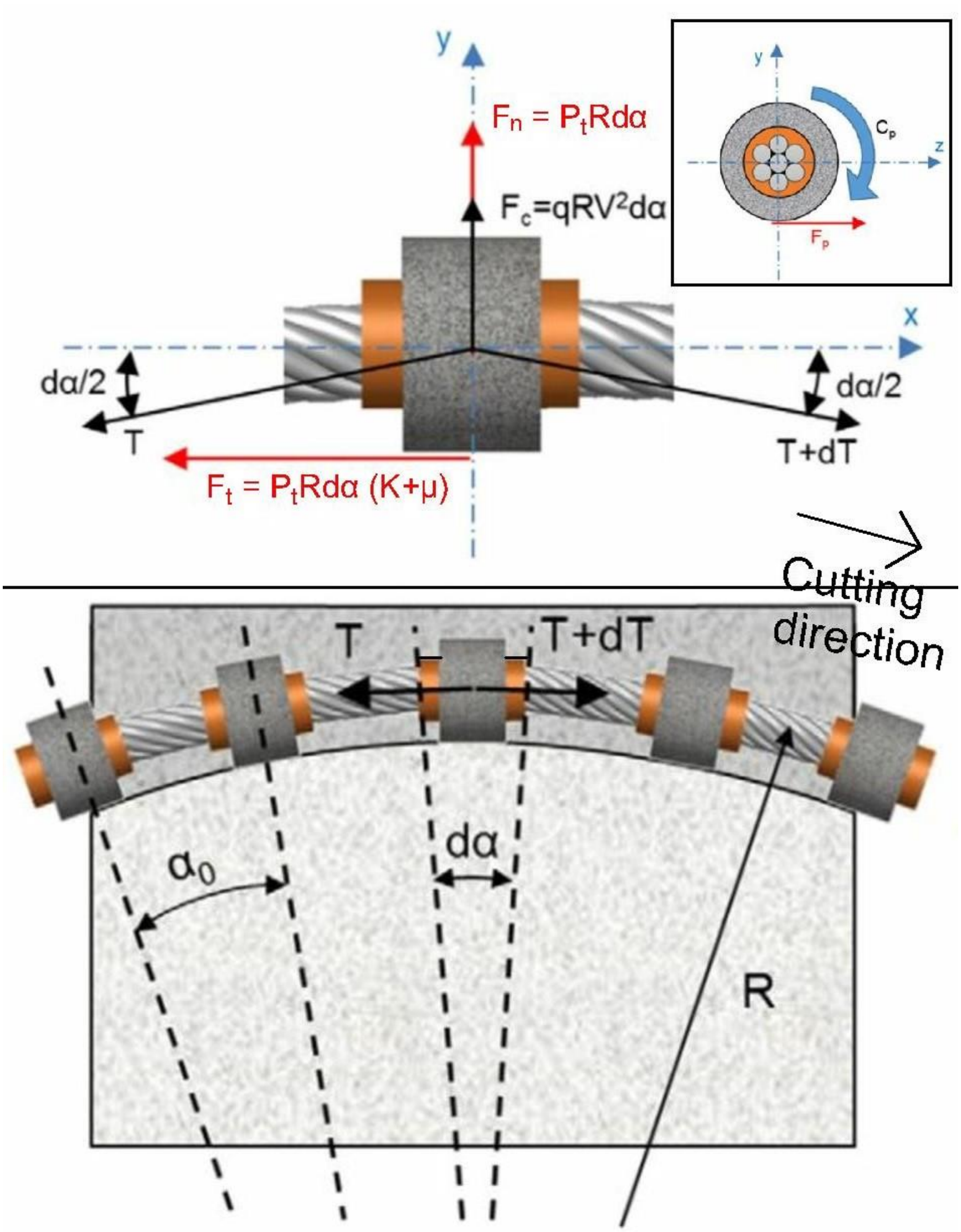

Figure 13. Basic model of diamond wire sawing and the forces acting on each bead during cutting (modified from Turchetta et al. 2017).

The acting forces presented in Figure 13 are (Turchetta et al. 2014; Turchetta et al. 2017):

1. T and T + dT are tension forces that represent the theoretical action exerted by the wire. The value of the forces increases along the cutting length due to the friction force.
2. F_n is the cutting force perpendicular to the wire direction. It is thus a normal force between the cutting tool and the stone and represents the reaction force on the material being cut. F_n is related to the strength of the material and to the linear cutting speed of the diamond wire. It can be calculated by using formula (2):

$$F_n = P_t R d\alpha \tag{2}$$

where P_t is the specific cut pressure on a unit length of the wire,
R is the radius of the arc-like curve that the diamond wire form, and
$d\alpha$ is infinitesimal arc portion that the single bead is bending during cutting.

3. F_t is the cutting force parallel to the wire direction. It is produced by the removal of the stone and the friction strength between the bead and material. There is a proportionality between the F_t and F_n. F_t can be calculated by using formula (3):

$$F_t = F_n (K + \mu) \tag{3}$$

where K is a constant representing the material removing, and
μ is the friction coefficient.

4. F_c is centrifugal force of the cutting tool and can be calculated as:

$$F_c = mv^2 d\alpha \tag{4}$$

where m is the mass of the single bead and the wire segment, and
v is the speed of the bead, i.e., the speed of the wire.

5. C_p is the theoretical torque imposed on the wire during its assembly by pre-twisting of the wire.
6. F_p is the force that opposes C_p.

According to Figure 13 and previously presented equations, the applied forces in the x and y directions of the cutting tool can be derived. The balance along x-axis can be calculated by using formula (5) (Turchetta et al. 2014; Turchetta et al. 2017):

$$-F_t - T cos\frac{d\alpha}{2} + (T + dT) cos\frac{d\alpha}{2} = 0 \quad (5)$$

and the balance along y-axis is:

$$F_n + F_c - T sin\frac{d\alpha}{2} - (T - dT) sin\frac{d\alpha}{2} = 0 \quad (6)$$

As dα can be considered as infinitesimal, it is possible to state that (Turchetta et al. 2014; Turchetta et al. 2017):

$$sin\frac{d\alpha}{2} = \frac{d\alpha}{2};\ cos\frac{d\alpha}{2} = 1 \quad (7)$$

Taking into account the previous statement, equations (5) and (6) become as following (Turchetta et al. 2014; Turchetta et al. 2017):

$$F_t = dT \quad (8)$$

$$F_n + F_c - Td\alpha = 0 \quad (9)$$

As the mass of the single bead is very small, the centrifugal force F_c can be considered as negligible. If in addition the tension T is considered as a function of angle α and F_n is substituted for equation (2), equation (9) becomes as (Turchetta et al. 2014; Turchetta et al. 2017):

$$P_t = \frac{T(\alpha)}{R} \quad (10)$$

As the pressure P_t is dependent on the radius R as shown in equation (10), it can be concluded that an increment in radius makes the cutting pressure decrease if the tension in the wire remains as same (Turchetta et al. 2014).

As pointed out earlier, the tension in the wire is not the same at all the points of the wire trajectory between the entry and the exit from the block due to the friction strength. For that reason, equation (10) can be derived further in order to determine the exact pressure in a specific point of cutting trajectory. This can be done by combining equations (8) and (9) into the following differential equation (Turchetta et al. 2014):

$$\frac{d(T-mv^2)}{T-mv^2} = d\alpha(\mathrm{k}+\mathrm{f}) \tag{11}$$

If (T - mv^2) is replaced by T* in equation (11) and the equation is integrated, it becomes as (Turchetta et al. 2014):

$$\int_{T_i}^{T_{i+1}} \frac{dT^*}{T^*} = \int_0^{\alpha_0} d\alpha(k+f) \tag{12}$$

where α_0 is the angle subtended by the considered infinitesimal part of the wire.

After resolving equation (12), it becomes as (Turchetta et al. 2014):

$$(T_{i+1} - mv^2) = (T_i - mv^2)e^{\alpha_0(k+f)} \tag{13}$$

$$T_{i+1} = T_i e^{\alpha_0(k+f)} + (mv^2)(1 - e^{\alpha_0(k+f)}) \tag{14}$$

If the angle is generalised to the generic angle α and since the centrifugal force is infinitesimal, it can be neglected, equation (14) becomes as following (Turchetta et al. 2014):

$$T_{i+1} = T_i e^{\alpha(k+f)} \tag{15}$$

By combining equations (10) and (15), general form for equation (10) is achieved (Turchetta et al. 2014):

$$P_t = \frac{T_i e^{\alpha(k+f)}}{R} \tag{16}$$

Equation (16) gives a specific pressure as a function of the bending radius R and the subtended angle α. As the specific pressure is changing along the wire trajectory, it gets values from a minimum, at the point where the tension T_i acts, to a maximum, at the point where the tension T_{i+1} acts. Figure 14 illustrate the increasing specific pressure. As it can be seen, maximum force is applied to the stone when the bead is about to leave the cutting surface. To calculate the minimum and the maximum pressures, the following equations can be used (Turchetta et al. 2014):

$$P_{t_{min}} = (T_{i+1} - T_i)\frac{1}{e^{\alpha_0(k+f)}-1} \tag{17}$$

$$P_{t_{max}} = (T_{i+1} - T_i)\frac{e^{\alpha_0(k+f)}}{e^{\alpha_0(k+f)}-1} \tag{18}$$

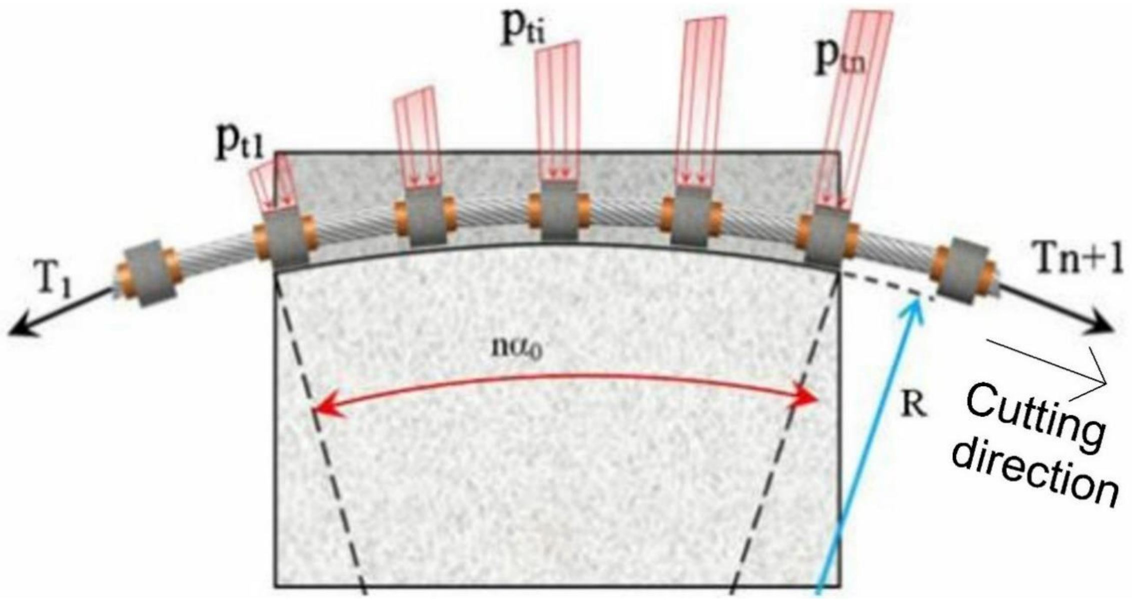

Figure 14. Increasing specific pressure acting on each bead in contact with the stone getting values from P_{tmin} to P_{tmax} (modified from Turchetta et al. 2014).

As can be seen from equations (17) and (18) and from Figure 14, wire tension is the factor that has the most impact on the bead's specific pressure and therefore also a huge impact on the cutting rate. This was proved also by the results of Kabir et al. (2015), who studied the relationship between a normal load applied to the bead and cutting rate. With a suitable wire tension, an optimum cutting rate can be achieved together with increasing production and a reduction of costs.

From all the forces present in the cutting, F_p is the only one acting out of the cutting plane (as shown in Figure 13). It is generated by torque C_p due to the rotational preload imposed on the wire during its manufacture. The C_p component is critical in the cutting process as it enables the rotation of the bead around its axis, generating a uniform bead wear. F_p force has, however, an unwanted effect as it tends to deviate the wire out of the cutting plane. So, in order to obtain an optimum situation, a balance between the rotational preload C_p and F_p component must be found in order to prevent unnecessary force acting out of the cutting plane. For optimal bead wear, the bead should rotate one complete round around its axis between the entry and the exit from the block (Turchetta et al. 2014).

In summary, there are multiple forces acting during cutting. Tension T is acting on the wire due to the feed force and the actual cutting is provided by the cutting forces F_n and F_t. Due to the mass of the single bead and the wire speed, there is also centrifugal force F_c acting on the bead. This is, however, infinitesimal as the bead mass is very small. In addition to these forces, there is also torque C_p acting on the wire, that enables uniform bead wear as the wire is rotating around its axis, and force F_p that is opposing the torque force.

4.4.1 Stress distribution of cutting

As pointed out, there is a difference in the wire tension between the inlet and the outlet section. Therefore, the shape of the cut surface is not symmetrical as more cutting is taking place at the outlet section. The difference in the wire tension between the sections is caused as the amount of friction increases along the cutting path and is thus seen as a higher cutting pressure on the outlet side. In other words, the pressure increases along the cutting direction from the entrance to the exit of the stone block (as shown in Figure 14). This process occurs for all the beads and, in this way, the actual cutting process happens (Almasi et al. 2015). Due to the increasing cutting pressure within the stone block, more cutting is taking place at the outlet intersection compared to inlet one (Ahn 2020; Lee et al. 2017). For this reason, the shape of the cut is not symmetrical (as shown in Figure 15).

The difference in the inlet and outlet tension is considerable: the inlet tension is only one-third of the outlet tension (Ahn 2020). This means that a lot of tension loss occurs during the cutting.

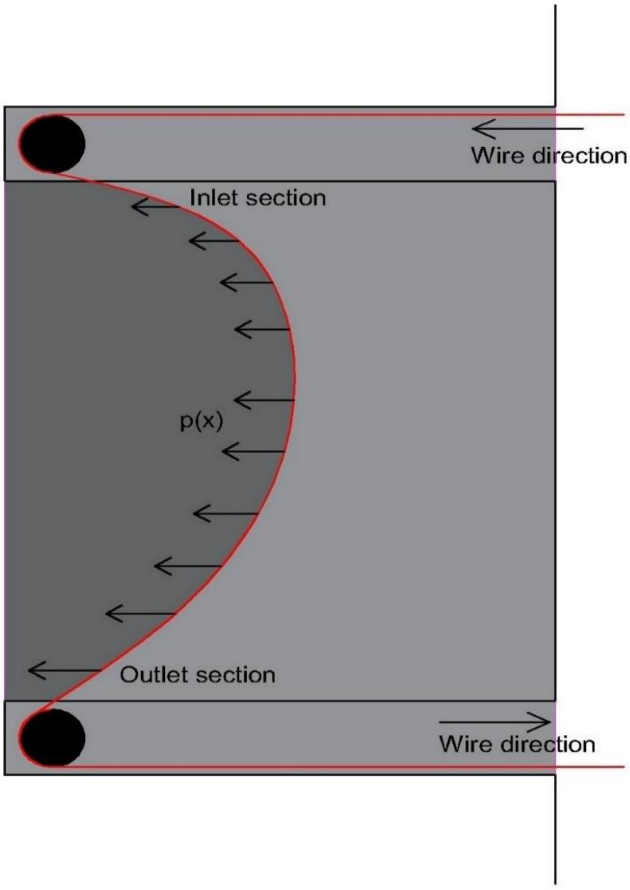

Figure 15. Stress distribution of wire saw cutting. Wire pressure expressed by p(x) (after Lee et al. 2017).

4.5 Cutting mechanism

As discussed in Paragraph 4.4, there are two cutting forces acting on the bead during the wire sawing: normal force F_n and tangential force F_t. These are the forces that provide the material cutting in the sawing process, which is formed by two mechanisms: the primary and secondary chip formation (Tönshoff et al. 2002). Diamond grains on the bead surface remove the material by scratching and cracking the stone surface and due to which the mechanism is more like a grinding process (Sadegheslam et al. 2013). Figure 16 illustrates the cutting mechanism of wire sawing.

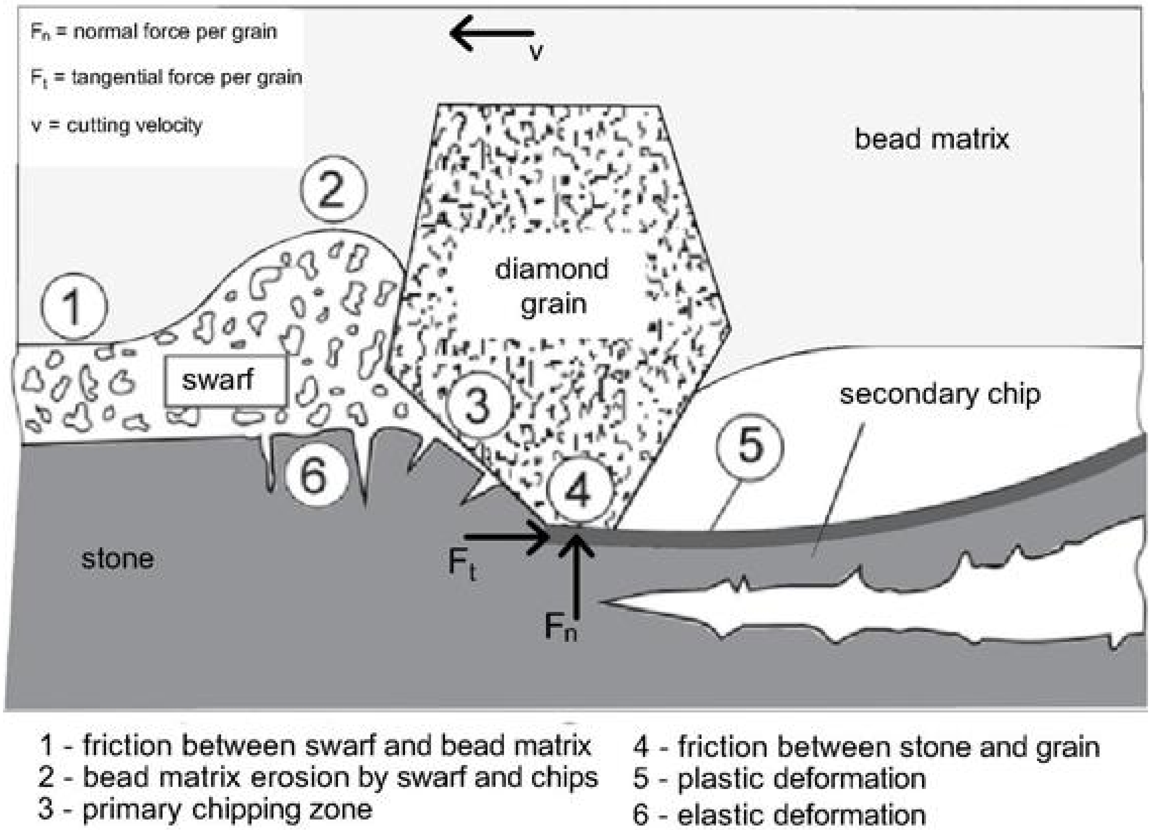

Figure 16. Cutting mechanism and interaction between the single diamond grain and stone (modified from Tönshoff et al. 2002).

At the front of a single diamond grain, tangential force F_t causes tensile and compressive stresses, which cause the cutting and formation of swarf. This is called primary chip formation, which is the principal mechanism of the cutting action. The zone for the primary chip formation is illustrated in Figure 16 at front of the diamond grain by the number 3. As the rock has elastic characteristics, it is necessary to reach a certain minimum grinding thickness in order to achieve the cutting action (Tönshoff et al. 2002).

When the diamond grain moves forward, the load on the stone surface is removed. This causes an elastic reversion, which leads to tensile stresses. This process affected by tensile stresses causes brittle fracture. That is the secondary chip formation, which is illustrated also in Figure 16 (Tönshoff et al. 2002).

Huang & Xu (2013) studied how cutting forces affect different parameters on wire saw cutting. The study was conducted for two different kinds of wire: brazed wire and sintered wire. The results related to material removal are shown in Figure 17. It can be seen from the graph that increasing cutting force increases the material removal rate. Also, it can be seen that at the same level of material removal rate, the tangential force is on average 50% lower than the normal force.

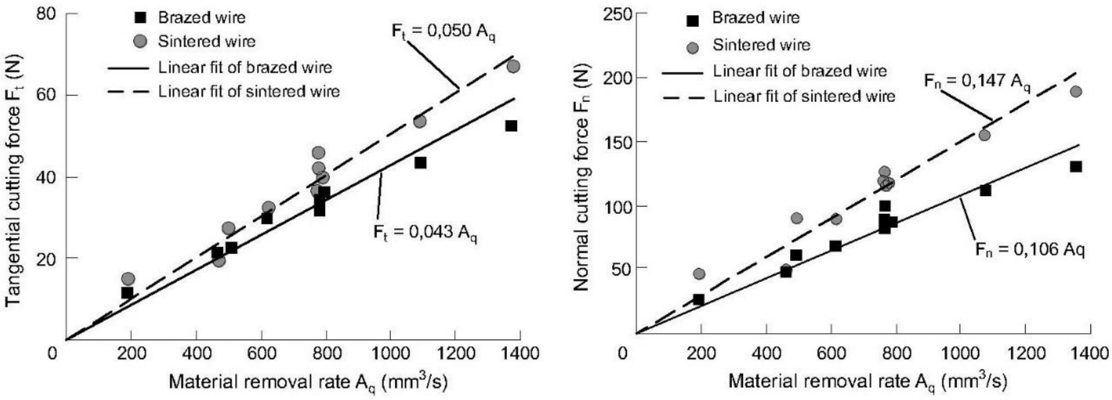

Figure 17. Cutting forces Ft and Fn versus material removal rate (after Huang & Xu 2013).

Compared to the cutting mechanism of diamond drilling, the mechanism in wire saw cutting is totally different. In diamond drilling, a sufficient linear speed is considered to be around 2.5–7.7 m/s combined with high pressure exerted on the drill bit. Together these cause the voluminous fracture of rock. Whereas, in wire saw cutting, a sufficient linear speed for the wire is usually 25–30 m/s and the pressure which a single diamond grain exerts on the stone is not obviously that high. For that reason, the process of wire saw cutting is not sufficient to penetrate the stone so that the voluminous fracture of stone would occur as in the case of diamond drilling. As the tension stresses decrease sharply with the increase of the depth, material fracture only occurs in a thin layer of the stone surface. Since the wire is continuously spinning at a high speed, the generated cuttings will be fragmented by the following diamonds as well, so the final cut debris is small in grain size. The swarf/cuttings generated by the cutting process are carried away by the flushing fluid (Liu et al. 2004; Tönshoff et al. 2002).

4.6 Specific energy

Specific energy is a property of the rock-cutting process, which describes the consumed energy to break a certain quantity of rock (Vogt 2016). Thus, it defines the level of power that is required in a cutting machine to work at a given rate (Vogt 2016). The unit for specific energy is J/m^3. Ahn (2020) presented the probable specific energy for wire saw cutting as illustrated in Figure 18. According to that study, specific energy varies from 1000 to 2000 MJ/m^3 and, if normalised according to the bead number, specific energy is approximately 38 MJ/m^3/bead. Specific energy as presented on the left of Figure 18 illustrates that the value changes according to the wire length. This might be misleading as it seems that the cutting procedure is least efficient when the wire length is large as the specific energy is maximal. This would be the case if the wire had only one bead performing the entire cutting process. For that reason, the specific energy was normalised according to the bead number, which gave a constant level of specific energy. If compared to the values of specific energy of other rock cutting methods (as shown in Figure 19), wire saw cutting is approximately at the same level as diamond drilling (Ahn 2020; Bieniawski et al. 2012).

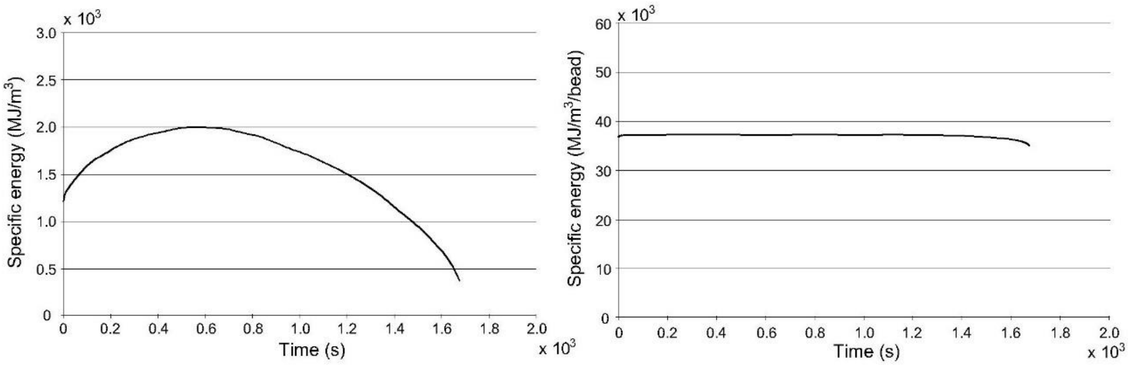

Figure 18. Estimated probable specific energy of wire saw cutting on the left and normalised according to the bead number on the right (after Ahn 2020).

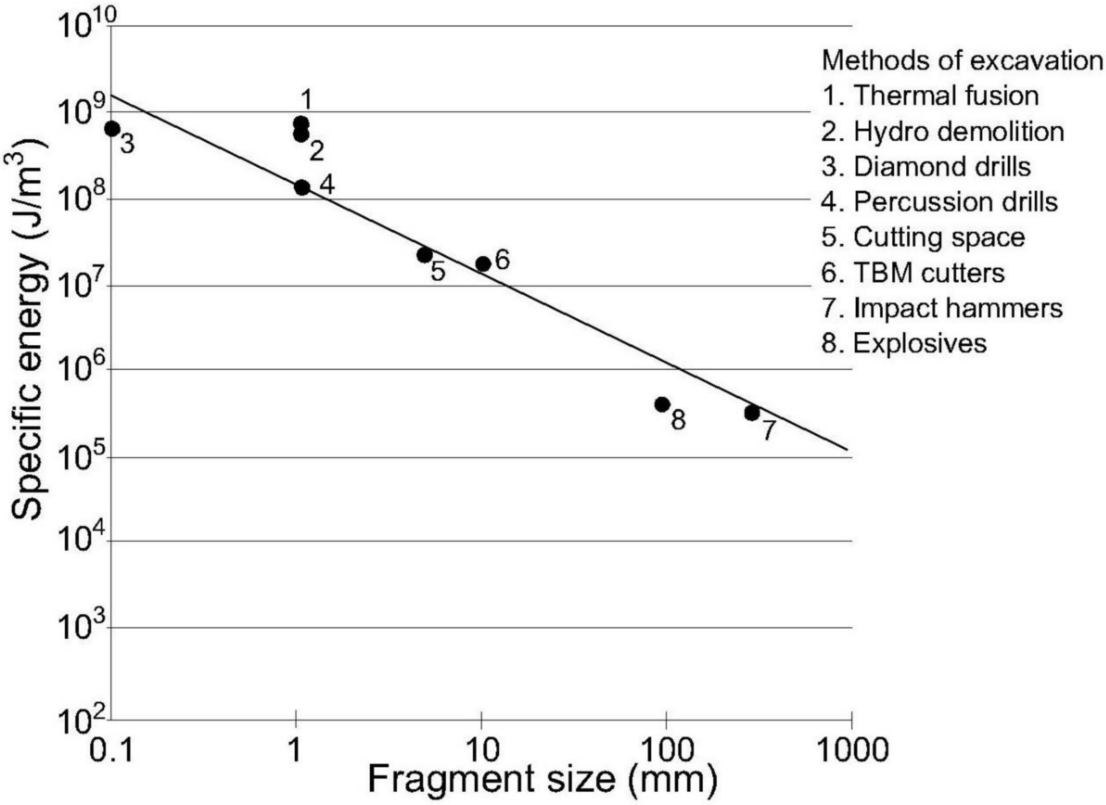

Figure 19. Specific energies of different rock excavation methods (after Bieniawski et al. 2012).

4.7 Power consumption

Based on the machines on the market, power typically varies from 45 to 75 kW. In this example, a power of 55 kW is used as the power to represent an average cutting machine. As described in Paragraph 5.1, the cutting rate in the blind-cut technique is approximately 2–5 m^2/h. Using these values, average power consumption per square metre can be estimated. The results are shown in Table 2.

Table 2. Rough estimate of power consumption per square metre of wire saw cutting in tunnelling. For reference: 1 kWh = 3.6 MJ.

	Machine power	55 kW
	Power consumption	55 kWh
Power consumption per square metre	Cutting rate 2 m^2/h	27,5 kWh/m^2
	Cutting rate 5 m^2/h	11 kWh/m^2

4.8 Wearing of the diamond wire

4.8.1 In general

In diamond wire sawing, operating parameters (such as load, cutting rate and linear velocity) together with mechanical and physical properties of the rock are factors that affect diamond bead wear the most. Under the same working conditions, the wear rate is strongly affected by the production rate and the characteristics of the rock. The operating parameters that directly affect the wear resistibility of the wire are feed speed and cutting speed (as illustrated in Figure 20) (Huang & Xu 2006; Zhang and Wang 2004). Among rock characteristics, rock hardness and rigidity are factors that have a strong effect on the wear rate; for example, the wear of diamond wire is much greater when cutting granite compared to a softer rock type (Najmedin Almasi 2017; Zhang & Wang 2004).

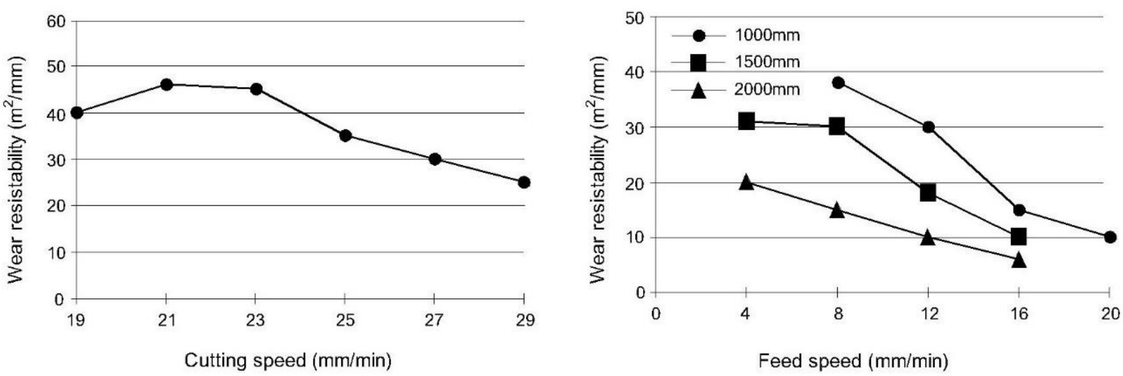

Figure 20. The effects of cutting speed and feed speed in wear resistibility of a diamond wire. 1000 mm, 1500 mm and 2000 mm are operational widths of the block for three different cuts (after Zhang and Wang 2004).

Under the correct operating conditions, the bead has a self-sharpening characteristic. It means that as the diamond particles wear down through the abrasive effect of rock, new particles progressively emerge from the matrix. For this reason, diamond particles and a metal powder matrix, which are used in a hot sintering process of manufacturing diamond beads, must have the correct properties in order to achieve the optimum wear between the matrix and diamond grains. If the wearing of the matrix is too fast, the diamond grains emerge too quickly and can, for example, be pulled out from the matrix. Alternatively, if the diamond grains wear much faster than the matrix, new sharp grains do not progressively emerge and cutting efficiency is reduced. The ideal condition is that the diamond particles are fractured in a controlled manner and, in that way, new sharp cutting edges progressively emerge from the matrix. This process continues until the active layer of diamond particles and matrix are completely worn out. After that, cutting becomes ineffective (Butler-Smith 1997).

4.8.2 Bead wearing

According to the literature, most bead wear takes place at the bead’s front end (Feng et al. 2019; Cardu & Michelotti 2008). Due to the cutting force applied to the bead and the resistance of the rock, momentum arises, which leads to higher pressure at the front part of the bead (Cardu & Michelotti 2008). For this reason, beads start to wear asymmetrically (as illustrated in Figure 21). If the conical wear of the diamond bead is significant, the life of the diamond wire will be significantly reduced. This can be avoided by a suitable cutting speed and feed rate, which enable work efficiency and reduce wear. The wearing of the diamond wire is also dependent on the load and temperature of the diamond particles, which further depends on the cutting speed and feed rate as well as cutting pressure and flushing (Feng et al. 2019).

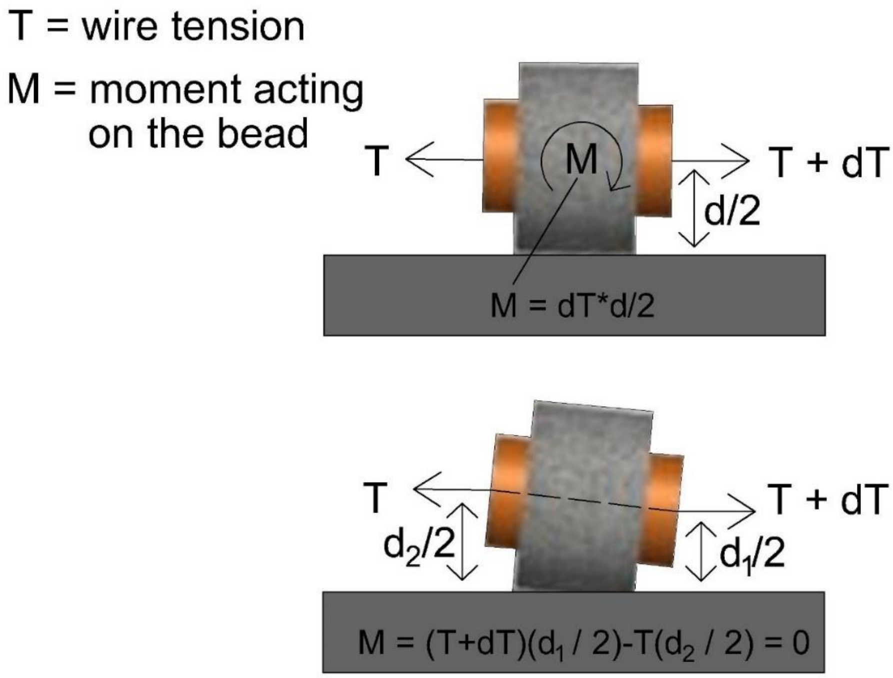

Figure 21. Wearing of the bead front end, as a result of which the bead tends to become conical (after Cardu & Michelotti 2008).

It is widely known that a wire saw with a larger bead spacing is more efficient but less durable than a wire saw with a smaller bead spacing (Ahn 2020; Mactech 2021). This is because the cutting effect relies on pressure to regulate the friction between the wire and the stone block (Mactech 2021). A wire with fewer beads requires a lower wire tension to produce the same amount of pressure and friction than a wire with more beads. For this reason, the wire will have a longer service life as it is not exposed to such high tensions. Alternatively, lower bead density increases the spacing between the beads and can thus increase wear on the wire structure (Mactech 2021).

4.8.3 Common types of wire breaks

During cutting the wire spins and tension force is applied on it. Basically, the main loads acting on the wire are tension, torque moment and bending moment (Huang & Xu 2006). These forces cause the wire to wear in the process. In addition to these forces, factors such as stress concentration, corrosion, abrasion, bending angle, bending frequency and bending radius occur and which might cause wire breakage of a part that is already worn (Huang & Xu 2006).

According to Huang & Xu (2006), two common types of wire breaks occur. The first is at the section of the transitional interface of the bead and the spacing material. Another common break is at the section between two adjacent beads, i.e. in the middle of the spacing material between the beads. According to their results, nearly all breaks resulted from the behaviour of the worn steel cable. Another phenomenon that was recognised was abrasion on the outer layer of the steel cable strands. This makes the spacing material and steel cable abraded and soften in the process and which, over time, will lead to fractures in the cable. According to the visit and interview at the site in Krångede, where wire saw cutting was used to cut a tunnel, there is also a third section where wire breaks can commonly occur. This section is the steel coupling connector that is used to connect the wire ends. For this reason, the steel connector needs to be changed regularly during the cutting operation. Common break sections and the steel connector are presented in Figure 22.

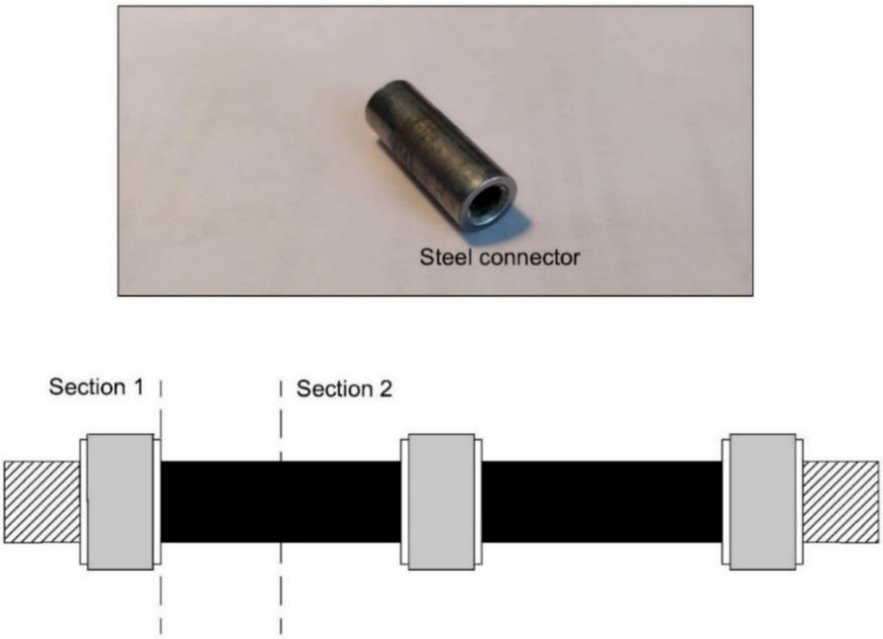

Figure 22. Common break sections (1 & 2) of the wire. The steel connector used to connect the wire ends is shown at the top of the figure. The connector needs to be replaced regularly during cutting in order to prevent failures of that part (after Huang & Xu 2006).

4.9 Flushing

Flushing is an important part of a successful cutting procedure. Usually, water is used as a flushing fluid and it is applied in the direction of the spinning wire. In addition to removing the cutting particles, flushing also cools the wire. Removal of the cutting particles optimises the performance of the cutting procedure and prolongs the wire's life. The amount of cutting increases correspondingly according to the cutting speed, so the flowrate for flushing should be adjusted according to the production rate. Flushing is also an important factor in dust management (Rossi 2006).

According to the results of Ge et al. (2004), flushing has a significant impact on cutting efficiency and force as it cleans the cutting chips from the wire saw surface. Cutting efficiency increases when flushing is used at the same time as cutting force decreases. The results are shown in Table 3. The results also show the effect of feed load on cutting efficiency and cutting force. With increasing feed load, cutting efficiency and force both increase.

Table 3. Cutting efficiency and cutting force in granite cutting with and without flushing (after Ge et al. 2004).

Feed load [N]		6	9	12	15
Cutting efficiency [mm/min]	Without flushing	5.16	7.2	10.65	12.9
	With flushing	5.46	9.0	11.4	14.4
Cutting force [N]	Without flushing	2.01	2.8	4.16	5.03
	With flushing	1.8	2.7	3.5	3.8

According to Padmore (2011) and Rossi (2006), excessive flushing can have the following consequences:

- overspilling,
- aquaplaning, i.e., the wire slides along the surface without penetrating it, and
- decreasing cutting efficiency.

The consequences of too little flushing can be (Padmore 2011; Rossi 2006):

- cable stripping,
- stacking,
- wearing,
- breakage,
- dusting,
- slot cut by the wire becoming obstructed, and
- overheating.

As can be seen also from these factors, the effects of too little flushing are more remarkable than the effects of excessive flushing. Thus, it is important to optimise the flowrate of flushing.

According to Rossi (2006), the development of wire sawing technology is largely based on experiment, which is also the case for flushing fluid flowrates; those are mostly based on experiment and practical experience rather than theoretical knowledge. The same thing was pointed out in 2020 by Ahn. In his research, he noted that in order to better understand the effects of flushing in the cutting process, further research is required. According to the study by Ahn (2020), there is a possibility that some other cutting fluid with lubricating properties other than water could offer better cutting performance.

5 VIBRATIONS

Blasting always causes ground vibrations as the total explosive energy cannot be fully targeted to break and fragment the rock. As a result, part of the energy is lost and one part of that is observed as a vibration (Ainalis et al. 2017). Ground vibrations can cause disturbance in an inhabited area and even damage to existing structures and buildings if the level of the vibration is not controlled. In fact, ground vibrations are considered to be the most common type of damage and environmental effect caused by blasting (Ainalis et al. 2017; Heiniö & Vanhatalo 1999). As one purpose of using wire saw cutting is to control blasting vibrations, it is important to understand the concept and how the pre-cut discontinuity made by wire sawing affects the propagation of blast waves.

5.1 Definition of blasting vibration

Blasting vibrations are generated as an explosive is detonated in a blasthole, which causes a shock wave that travels to a rock mass (Zhang 2016). As a rock is inert material, the shock wave rapidly decays to an ordinary stress wave. This stress wave starts to propagate along the rock mass. The distance of the propagation and amplitude depends on multiple factors, which makes it hard to predict the level of the vibration (Ainalis et al. 2017; Avellan et al. 2017). Some of these factors are controlled and some uncontrolled, such as site-specific variables. As stress waves caused by a blast can travel even great distances, it is important to predict and control vibrations in the best possible manner.

Waves caused by an explosion can be divided into body waves and surface waves (Heiniö & Vanhatalo 1999; Zhang 2016). Body waves include two types of waves, P-waves and S-waves, and surface waves in rock blasting include mainly Rayleigh waves. The main difference between the waves are the wave form and propagation velocity. Body waves mainly propagate within a rock mass, whereas surface waves mainly travel on or close to the surface, with rapidly decreasing intensity according to depth (Heiniö & Vanhatalo 1999). P-waves travel with the highest velocity and S-waves roughly one-half of that. Due to the differences in the propagation velocity, the ground vibrations caused by blasting are often a mixture of two or more waves (Zhang 2016).

Ground vibrations generated due to blasting can be also divided into two distinct regions: near-field and far-field regions (Ainalis et al. 2017; Zhang 2016). The near-field region contains the area close to the blasthole and is the most complicated region. Within this area extremely high pressures are applied to the blasthole in order to crush, fracture and move the rock mass. The remaining energy after that is propagated along the rock mass and is observed as a vibration in the far-field regions. The difference between these regions is mainly in the amplitudes and waveforms of the waves. Due to these differences, it is possible to use different techniques in order to reduce ground vibration. A pre-cut discontinuity made by wire saw cutting is one such method.

5.2 Effects of ground vibration

When blasting is carried out near urban areas, stress waves caused by blasting produce dynamic stresses on the structures, buildings or underground excavations along their path (Avellan et al. 2017). The most typical types of damage that occur are elongation, shearing and bending (Heiniö & Vanhatalo 1999). These may appear, for example, as a crack in the pad footings of buildings. Factors affecting possible structural damage are, for example, the age of the structure and the natural frequency and sensitivity of the structure or equipment (Ray & Dauji 2019). Risk analysis for certain circumstances is carried out by a vibration and blasting consultant or someone with experience and knowledge of the field. As the propagation of stress waves is always site dependent, it is recommended that blasting tests are performed, if possible, in order to obtain information before starting the production (Heiniö & Vanhatalo 1999).

Permitted vibration limits in a certain area are affected by many factors, of which some of the most important are (Heiniö & Vanhatalo 1999):

- vibration resistance of the building materials,
- general condition of the building,
- duration and character of the vibrations,
- presence of sensitive vibration equipment,
- foundations,
- condition of foundations,

- propagation characteristics of waves in rock, earth and building material, and
- replacement costs / highest likely repair costs.

Blasting vibrations can be calculated and predicted using different formulas, but the effects of the ground vibration are the most typically quantified by the following factors: peak particle velocity (PPV), its duration and frequency (Avellan et al. 2017; Dauji 2018). PPV is the maximum amplitude value of the ground vibration and its unit is mm/s. Moreover, stress and transmitted energy are parameters that should be considered but, in practice, vertical particle velocity is used mostly in vibration control (Vuolio & Halonen 2012; Zhang 2016). The reason, according to research, is that PPV is found to be the most vital factor for correlating increasing levels of damage caused by blasting (Ainalis et al. 2017; Avellan et al. 2017; Xia et al. 2013). That is why PPV has been found to be the best and most practical description for defining potential structural damage (Heiniö & Vanhatalo 1999). Particle velocity can be estimated with the following equation (19) (Heiniö & Vanhatalo 1999):

$$v = 2\pi fA \tag{19}$$

where v is particle velocity (mm/s),
f is frequency (periods/sec), and
A is amplitude (mm).

Vibration acceleration is another equation (20) that is used when calculating vibrations caused by blasting. It is used especially for sensitive structures such as computers and hospital equipment (Heiniö & Vanhatalo 1999):

$$a = 4\pi 2f2A \tag{20}$$

where a is acceleration in g (9.81 m/sec^2).

5.3 Blast vibration norms and legislation

In order to control and protect against the consequences of ground vibrations, there are norms and legislation setting permissible vibration limits. These regulations are country specific depending on, for example, the type of construction material used. Due to differences in bedrock and construction materials, damage criteria and propagation equations are always country specific (Avellan et al. 2017). In Finland, vibration guideline values are defined in RIL 253-2010, Rakentamisen aiheuttamat tärinät (Vibrations caused by construction) (Hakulinen & Vuento 2010). The guideline value defines the allowable PPV in mm/s.

Finnish limit values for peak particle velocity can be calculated with the following equation (21) (Heiniö & Vanhatalo 1999):

$$v = F_k v_1 \tag{21}$$

where v is particle velocity,
F_k is building factor, and
v_1 is peak particle velocity on different distances for structures and buildings that have been founded on different materials/vertical component.

Structural coefficient factor F_k used in equation (21) is presented in Table 4. The value that the factor gets is affected by different structural materials and vibration sensitiveness. Some of the values are based on past experience and test series, such as the value for curing concrete. Also, the values for electrical cables, pipelines and rock masses are mostly based on experience. In Finland, a higher value for F_k may be permitted by a qualified consultant. A and AA competence classes present in Table 4 are official vibration expert classifications issued by FISE (Qualification of Professional in Building Sector in Finland) (Heiniö & Vanhatalo 1999; Weman 2015).

Table 4. Finnish structural coefficients factors (after Hakulinen & Vuento 2010; Heiniö & Vanhatalo 1999).

Structure	Structural coefficient Fk (competence class A)	Structural coefficient Fk (competence class AA)
1. Heavy structures like bridges, piers, etc.	1.75	2.00
2. Concrete and steel buildings, rock caverns with shotcrete reinforcement.	1.25	1.50
3. Office and commercial buildings of brick and concrete. Wood-frame houses on concrete or stone foundation.	1.00	1.20
4. Brick and concrete residential buildings with no light concrete, limestone-sand brick, etc. Rock caverns with no shotcrete reinforcement. Curing concrete > 7 days old. Electrical cables, etc.	0.85	1.00
5. Building with light concrete structures. Very vibration sensitive buildings, such as museums, churches and other buildings with high vaults and great spans. Curing concrete 3–7 days old.	0.55	0.65

After the limit value for peak particle velocity is calculated, the following equation (22) can be used to calculate the maximum instantaneous charge (MIC) (Weman 2015):

$$v = k\sqrt{\frac{Q_m}{R^{1,5}}} \tag{22}$$

where v is vibration velocity (mm/s),
k is transmission factor, constant depending on the homogeneity of the rock and the presence of faults and cracks (typically known from previous blasts or test blasts estimated by distance and rock/soil type),
Q_m is instantaneously detonating charge (kg), and
R_d is distance (m).

5.4 Vibration reduction by a slot made around the blasting centre

As blasting-induced vibrations cannot be avoided, there are different methods for reducing the amount of vibration. Wire saw rock cutting together with blasting is one method for that. The effectiveness of the method in vibration reduction is based on a slot made around the blasting area. This slot prevents the propagation of blasting-induced seismic waves through the unconnected area. According to Zhang (2016), such an empty space between a blast source and a region where vibrations have to be controlled will markedly reduce the vibrations. This kind of slot can effectively stop or at least significantly reduce stress waves propagating from a blasting source to the area of reduced vibration limits (Zhang 2016).

When seismic waves travel to a free surface, the waves do not propagate through it (Song et al. 2014; Zhang 2016). Rather, the waves are reflected and refracted from the free surface and will thus be trapped inside the tunnel section (as illustrated in Figure 23). This means that the characteristics of the propagating waves will be changed (Lee et al. 2016). This is why wire saw cutting together with blasting can be a very effective excavation method for vibration reduction, as the free surface around the tunnel perimeter can completely separate the tunnel section from the rock mass around it and prevent the propagation of seismic waves (Song et al. 2014).

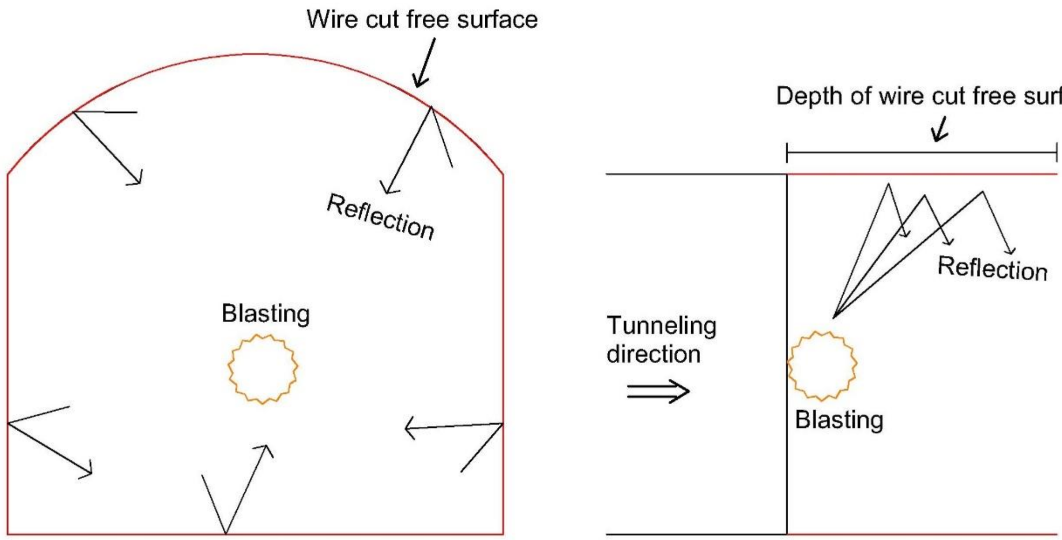

Figure 23. Tunnel blasting with wire sawn tunnel circumference. Transversal view from the tunnel section on the left and longitudinal view on the right (after Song et al. 2014).

For simplicity, if a one-dimensional wave propagation across a discontinuity is considered, the corresponding magnitude of the transmission coefficient is (Schoenberg 1980):

$$|T_p(\omega)| = \left| \frac{\frac{2k_p}{Z_p}}{-i\omega + \frac{2k_p}{Z_p}} \right| \tag{23}$$

where T_p is transmission coefficient,

ω is circular frequency of the incident wave,

k_p is stiffness of the discontinuity, and

Z_p is seismic impedance.

And for the one-dimensional wave propagation across a discontinuity, the corresponding magnitude of the reflection coefficient is the following (Schoenberg 1980):

$$\left|R_p(\omega)\right| = \left|\frac{i\omega}{-i+\frac{2k_p}{Z_p}}\right| \tag{24}$$

where R_p is reflection coefficient.

Seismic impedance in the equations (6) and (7) is expressed by (Schoenberg 1980):

$$Z_p = \rho_r C_{ws} \tag{25}$$

where ρ_r is density of the rock, and
C_{ws} is compressional wave speed.

According to the equations (23) and (24), it can be calculated that when k_p has the value of zero because of the pre-cut surface, all the waves are reflected at the free surface and thus the PPV will be significantly reduced around the tunnel section (Lee et al. 2016). Theoretically, this means that when k_p is zero, the transmission of the incident waves is not possible. This proves that the pre-cut surface will effectively diminish vibrations caused by blasting. The analytical expressions related to the equations (23) and (24), and numerical tests were confirmed by Lee et al. (2016). One important thing that Lee et al. (2016) pointed out was that if the pre-cut discontinuity collapses as soon as the blasting wave reaches it, a fair number of waves will propagate into the surrounding rock masses. In this case, the blasting vibrations would not be diminished as designed. This is why it is important to pay attention to the number of charges used when using the pre-cut method.

Song et al. (2014) used an abrasive waterjet technique to create a slot along a tunnel perimeter. According to results in that study, the precutting free surface prevents the propagation of the seismic waves and thus have a significant effect on the reduction of the peak particle velocity. The vibration reduction rate according to that study was even ~57%. Despite this, the technique for executing a free surface in the study was not wire saw cutting, and it proves that the pre-cut discontinuity will markedly reduce the propagation of vibration waves. The study also pointed out that, as the depth of the precutting free surface increases, the blasting-induced vibration decreases at the tunnel face and behind the tunnel face. This means that the use of the pre-cut discontinuity also provides that the excavation damaged zone and loosening earth pressure above the tunnel are reduced. Thus, tunnel quality and stability will be better. This was demonstrated also by Christiansson et al. (2014) in Sweden. According to that study, there were no blast-induced fractures in the sawn surface, which was confirmed by taking ground penetrating radar measurements and sawing a 75 cm deep rock plug from the tunnel bottom.

According to results of Song et al. (2014), the effectiveness of vibration reduction with pre-cut discontinuity is related more to the depth of the precutting free surface than its thickness. For this reason, their conclusion was that a thin and deep slot is an effective way for the reduction of blasting-induced vibration as well as enabling a cost-effective tunnelling process. According to their results, a conclusion can be drawn that wire saw cutting can also be effectively used to reduce blasting-induced vibration as the thickness of the pre-cut discontinuity does not affect the results in vibration reduction that much.

When blasting is carried out, it causes first a detonation wave, of which the waveform is a shock wave. This shock wave starts to propagate through the rock mass but will rapidly decay into a compressive stress wave. When this compressive stress wave reaches a free surface, it is reflected into a tensile stress wave (Zhang 2016). It is well known that the tensile strength of the rock is much smaller than its compressive strength, and this is why tensile stress plays an important role in rock fragmentation (Menacer et al. 2015; Zhang 2016). Usually, the compressive strength of the rock is from 8 to 15 times greater than the tensile strength, with an average of 10 (Zhang 2016). According to these results, a pre-cut surface made by wire saw cutting can also increase fragmentation efficiency as the reflecting waves from the wire cut surface turn into tensile waves. Waves will also be trapped inside the tunnel section, which means the waves will resonate at the target surface to be blasted (Song et al. 2016). Song et al. (2016) pointed out that, in this way, it possible to break a stronger rock mass with a lower blasting pressure, which means better effectiveness in the blasting procedure.

Even though according to theoretical knowledge the pre-cut discontinuity should prevent the propagation of vibration waves almost entirely, it has not obviously been so in real cases. According to a study conducted in Sweden, PPV was about 20% lower when comparing the results of normal tunnelling blasts and blasting with wire sawn tunnel circumference (Christiansson et al. 2014). The peak value was about 3 times lower than the maximum value of the reference case. Lee et al. (2016) predicted the vibration reduction to be 50% lower when using pre-cut surface. The result was calculated from the numerical experiment. As can be seen, wire saw cutting can be effectively used to reduce vibrations, but research is still needed to study the actual effect of it in vibration reduction.

Christiansson et al. (2014) also made the observation that more reblasting was needed due to large, oversized fragments. They drew the conclusion that the reason was probably due to part of the explosive gases being ventilated through the four corner holes and wire sawn slots. For this reason, part of the explosive energy was lost and did not contribute to rock fragmentation. Therefore, they changed the drilling and charging plan with the oblique holes towards the sawn slit. This worked better and the following rounds were blasted with good results. This proves the importance of using a suitable drill and blast plan when using pre-cut discontinuity around the tunnel circumference. Gas penetration through the fractures, wire sawn slot and corner holes is illustrated in Figure 24 according to Christiansson et al. (2014).

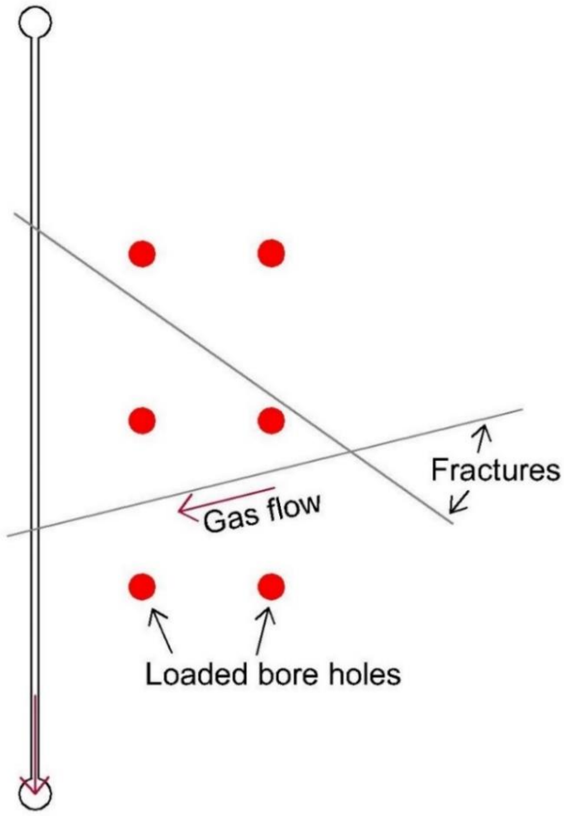

Figure 24. Gas flow through the fractures, wire sawn slot and corner holes (after Christiansson et al. 2014).

In summary, it can be concluded that blasting-induced vibrations can be reduced significantly with pre-cut discontinuity as the waves cannot propagate through the free surface. The effectiveness of vibration reduction is hugely dependent on the depth of the pre-cut surface, so it has to be deeper than the blastholes in order to effectively reduce the vibrations. Due to the enclosed tunnel area and reflecting tensile waves, rock fragmentation will be more effective. Therefore, it is important to consider these factors also in the drill and blast plan, so that an unnecessary number of drill holes and/or explosives are not used. If the number of drill holes and/or explosives can be reduced, it will also positively affect the levels of vibrations. Furthermore, the execution time for drilling and charging will be shorter. In addition, the use of pre-cut discontinuity together with blasting will ensure that the excavation damaged zone can be minimised and the tolerance in excavation accuracy is at a high level. These factors support the conclusion that effectively performed wire saw cutting can be a very effective method for vibration reduction.

6 WIRE SAW CUTTING IN KRÅNGEDE

6.1 Krångede

Krångede hydropower plant is an underground power plant located along the river Indalsälven in Jämtland, Central Sweden. It is the largest hydropower plant of Fortum AB and contains six turbines. Annual production of the plant is over 1600 GWh. Construction of the powerplant began in 1931 and it has been operational since 1936 (EPD International AB 2018).

In order to increase the accessibility of the power plant, a new access tunnel is being excavated by YIT Sverige AB just next to the already existing machine hall (as shown in Figure 25). The tunnelling project is complex as the constantly running power plant is located close by. The distance between the new tunnel and the machine hall is just 9 metres. The tunnelling work consists of a 600-metre long tunnel, of which about 120 metres is to be excavated by the combination of wire saw cutting and the D&B method. The beginning of this 120-metre-long section is shown in Figure 25 on the right as the new access tunnel (YIT 2021).

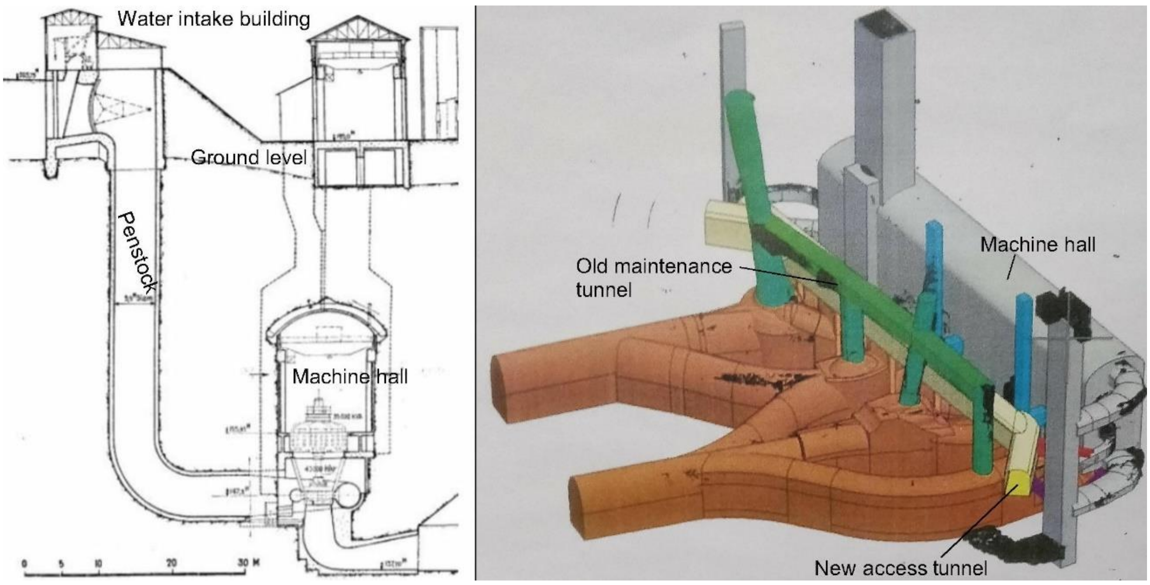

Figure 25. Illustration of the Krångede underground hydropower plant (modified from EPD International AB 2018; Material from Krångede 2021).

6.2 Implementation of wire saw cutting in Krångede

According to site manager Pyykkönen (2021), the main reason for using wire saw cutting together with the D&B method in Krångede is to limit vibrations. The machine hall, where the six turbines are located, contains vibration sensitive computer equipment. If the computers were to shut down due to too high blasting vibrations, the whole production of the power plant would be interrupted. For this reason, the vibrations must be controlled to remain below the acceptable level of 30 m/s^2. As the limiting factor for vibrations is sensitive computer equipment, the acceptable limit is presented as acceleration, as pointed out also in Chapter 5 concerning blasting vibrations. Another factor is that the new tunnel is surrounded by 90-year-old underground excavations, of which the closest are just 1.8–1.9 metres away from the new tunnel. These two are the vertical shafts presented in blue in Figure 25. As the surrounding excavations are located so close by and are to be excavated using old-fashioned techniques, extreme care must be taken with regard to the vibrations for this reason as well. Wire saw cutting together with the D&B method was chosen to implement these requirements. According to site manager Pyykkönen (2021), slot drilling was also considered as an option at the beginning of the project; however, the choice was made to use wire saw cutting. The wire saw cutting work is being done by Norwegian contractor company Diamant Wire Teknikk AS.

Wire saw cutting is implemented for the bottom and side walls of the tunnel. This was considered to be sufficient in order to keep the vibrations below the acceptable level. The dimensions of the cuts for the side walls are 4.7 m in height and 5 m in width for the floor. The aim is to saw 20 metres of tunnel in length at once. To implement wire saw cutting, four holes must be drilled first in the corners of the tunnel section. The length of these holes must be the same as the previously mentioned length of the target section, that is, usually 20 metres in Krångede. Smaller holes are drilled first in order to keep the acceptable tolerance in the precision of the holes, which is just 10 centimetres of deviation per 100 metres of drilling. This makes the drilling procedure sometimes difficult, especially in more fractured zones, as the drill bit tends to deviate. The first stage of the drilling is to be done by core drilling so the samples can be used also to analyse the rock mass. This will help complete the following work phases as the zones of fractures and weaker areas can be predicted. After that, the drilled holes are reamed to a larger size of

255 mm in diameter. This is done in order to enable the installation of the two rods, which include the guide pulleys and the cutting wire, into the holes. The reamed hole and the end of the rod with the guide pulley are presented in Figure 26 (Pyykkönen 2021).

Figure 26. Reamed hole on the left and the rod with a guide pulley on the right, which is then installed into the hole together with the wire. The diameter of the hole is 255 mm, and the diameter of the guide pulley is 200 mm.

After the four holes are drilled and reamed, installation of the cutting equipment can be started. The first part of the equipment installation is the mounting of the rods together with flushing hoses into the corner holes. At both ends of the rods are guide pulleys, through which the cutting wire runs, as described in Paragraph 3.1.3. After that, rails can be positioned on the tunnel floor as well as the cutting machine on the rails. These must be positioned so that the wire runs in a straight line. The wire ends are then connected by a steel connector and the wire is mounted on the drive wheel of the machine. Figure 27 shows the set-up for carrying out the cutting. In total, the installation of the cutting equipment should take approximately 12–18 hours (1–1.5 work shifts).

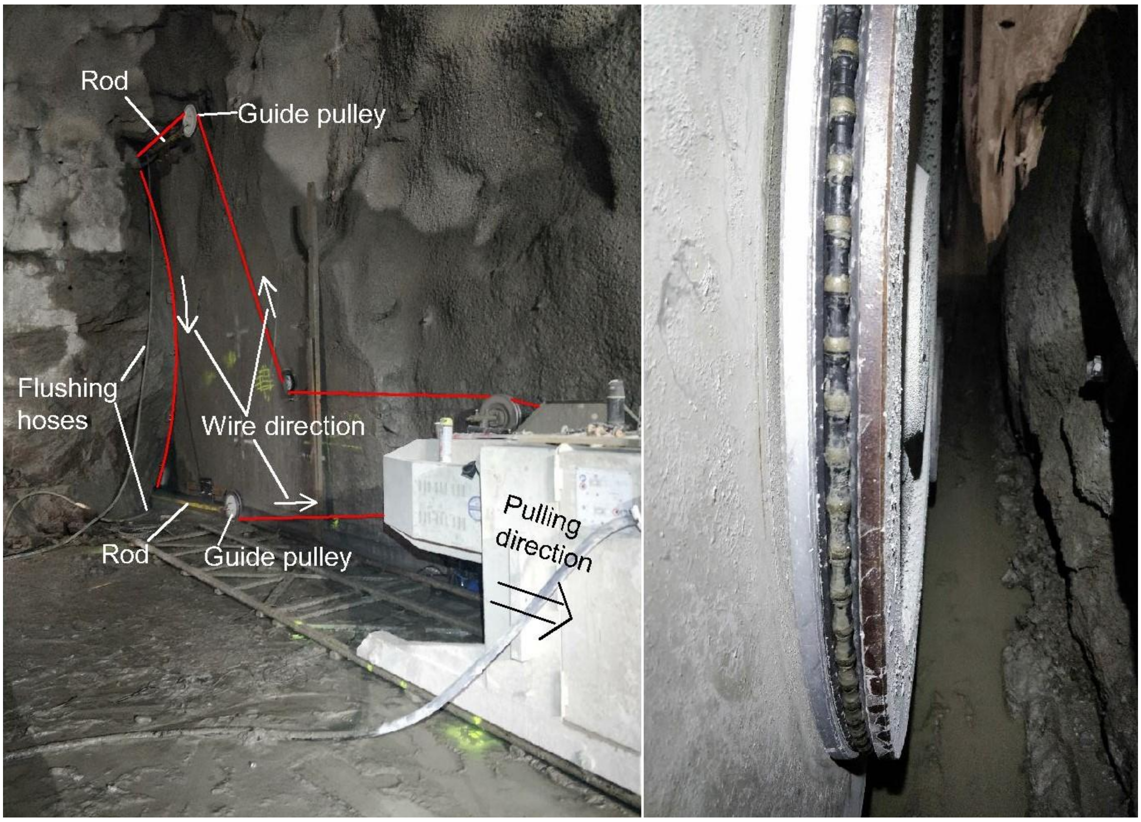

Figure 27. Installed equipment for cutting the right side wall. Cable lines highlighted for demonstration purposes. The picture on the right shows the mounted wire on the drive pulley of the machine.

The aim in Krångede is to wire saw 20 metres of tunnel at once. The longest round they have been able to cut has been 25 metres. The length of the cut depends a lot on how well the drilling of the corner holes and the actual cutting work has succeeded. The longer the cut can be performed at once, the more efficient it is in terms of cost and time, since the number of stages for equipment installation decreases. However, there have also been rounds they have been only able to cut 2.5 metres before the wire has got stuck in the slot. If the wire cannot be removed, cutting cannot be continued for this part anymore. This means that the remaining sides must be cut at least up to the same level as the slot with the stuck wire. After that, the D&B method can be carried out for this part. This problem has occurred a few times in Krångede during the ongoing project (Pyykkönen 2021).

6.2.1 Example case from the tunnel section cut by wire sawing in Krångede

During the visit on site, the area for the floor cut, left wall, and right wall were, respectively, 65 m^2, 63,5 m^2 and 54,05 m^2. The target length for each side was approximately 14 metres. In total, it took 7 days (14 work shifts) to complete the wire saw cutting for this section of the tunnel.

The bottom part was cut first because, if the side walls were cut before that, gravity could affect the block more and complicate the cutting of the floor. By cutting the bottom first, the risk of the wire getting stuck could be reduced. The floor cut of 65 m^2 was done during five work shifts, of which the first shift was used almost completely (10 hours) for installing the equipment. The actual cutting work took approximately 40.5 hours for the 5 x 13 m section, which gives an average cutting rate of 1.6 m^2/h. Water was used as the flushing fluid and the supply speed was adjusted by ball valve, so the flowrate was not measured in any way. The following problems occurred during cutting:

- On the second day, the left rod had to be taken out as the steel connectors of the wire ends were worn significantly in a short time and it seemed that the guide pulley at the bottom of the left corner hole was not spinning properly. The rod was taken out and the guide pulley was changed for a new one since the bearing was in poor condition. Also, the corner hole seemed to be full of drill cuttings, so the hole had to be cleaned with a high-pressure water jetting truck. As the truck needed to be ordered to the site, there was a period of 7.5 hours of downtime in production.
- At the end of the work shift on the third day, the wire began to bounce strongly, as if it were getting stuck occasionally while spinning. The machine had to be stopped but nothing showed up in troubleshooting. The machine was restarted, but the same thing happened. The conclusion was that the wire had slipped off the guide pulley at the bottom of the hole. Cutting had already reached 13 metres of the total of 14 metres, so the decision was taken to stop the cutting of the floor at that stage. It would have been too time consuming to remove the rod, reposition the wire and reinstall the rod as there was only one metre left to complete.

After the floor, the right side wall was cut next. The cutting of this side, with a total cut area of 63.45 m^2 (4.7 x 13.5 m), took a total of four work shifts, of which the first and a few hours of the second were used to remove the equipment from the bottom cut and reinstall it for the side wall cut. During the cutting there no problems as with the floor cut, so the cutting proceeded without any disruption. The cutting was done halfway through the fourth work shift. In total, the actual cutting work took just about 24 hours. This gives a very good cutting rate of an average of 2.65 m^2/h.

The last part to cut was the left side wall. The total cut area for this part was 54.05 m^2 (4.7 x 11.5 m). The total time for executing this cutting was five work shifts, of which the equipment removal from the right side and reinstallation on the left side took approximately 12 hours. There were no problems during the cutting of this side, but the operators did mention that the cutting proceeded pretty slowly. The total time used for the cutting work was approximately 33 hours, which gives a cutting rate of 1.6 m^2/h.

It is worth mentioning from the cutting rates presented so far that they are all just rough estimates, but they do give a good idea of how much cutting is done on average during one work shift and, furthermore, how long it took to complete the cutting for this section of the tunnel. The purpose was also to describe how the cutting was proceeding and what problems were encountered. More precise measurements for determining the exact cutting rate would have needed more preparation beforehand and equipment for taking those, which was not possible in this case.

According to the operating personnel, cutting rates vary a lot from site to site as rock conditions change. In their opinion, a good cutting rate in Krångede is 1 m^2/h, so the cutting rates presented here are on average considerably more than this. According to site manager Pyykkönen (2021), the cutting rate has commonly varied from 10 to 25 m^2 during one work shift (12 hours), with an average value of approximately 15 m^2, which is 1.25 m^2/h. This is at the same level as discussed previously based on the visit.

6.3 Drilling and charging

After all the three sides were cut, drilling and charging could begin. It is usually performed in rounds of 2.5 metres at a time in order to keep the vibrations below the acceptable level of 30 m/s^2. The computer equipment located in the power plant's machine hall contains vibration meters that are continuously measuring vibration levels. The distance between the new tunnel and the machine hall is approximately 9 metres, and the distance to the vibration meters, which are located on the opposite side of the machine hall, is approximately 20 metres. With this combination of wire saw cutting and the D&B method, vibrations remained below the acceptable level without any problems.

In order to maximise the effect of vibration reduction in blasting, the cut hole was located in the bottom left corner, which is the furthest point from the machine hall located on the right-hand side of the tunnel. The corner hole drilled for the rod of the wire cutting machine was used as a cut hole (255 mm in diameter). From the left bottom corner, the blasting proceeded to the right and upwards (as illustrated in Figure 28) by values from 0 to 6200, which are delay times in milliseconds for the ignition of the blast holes. Pipecharges were used as explosive as they were considered to be more precise in vibration control.

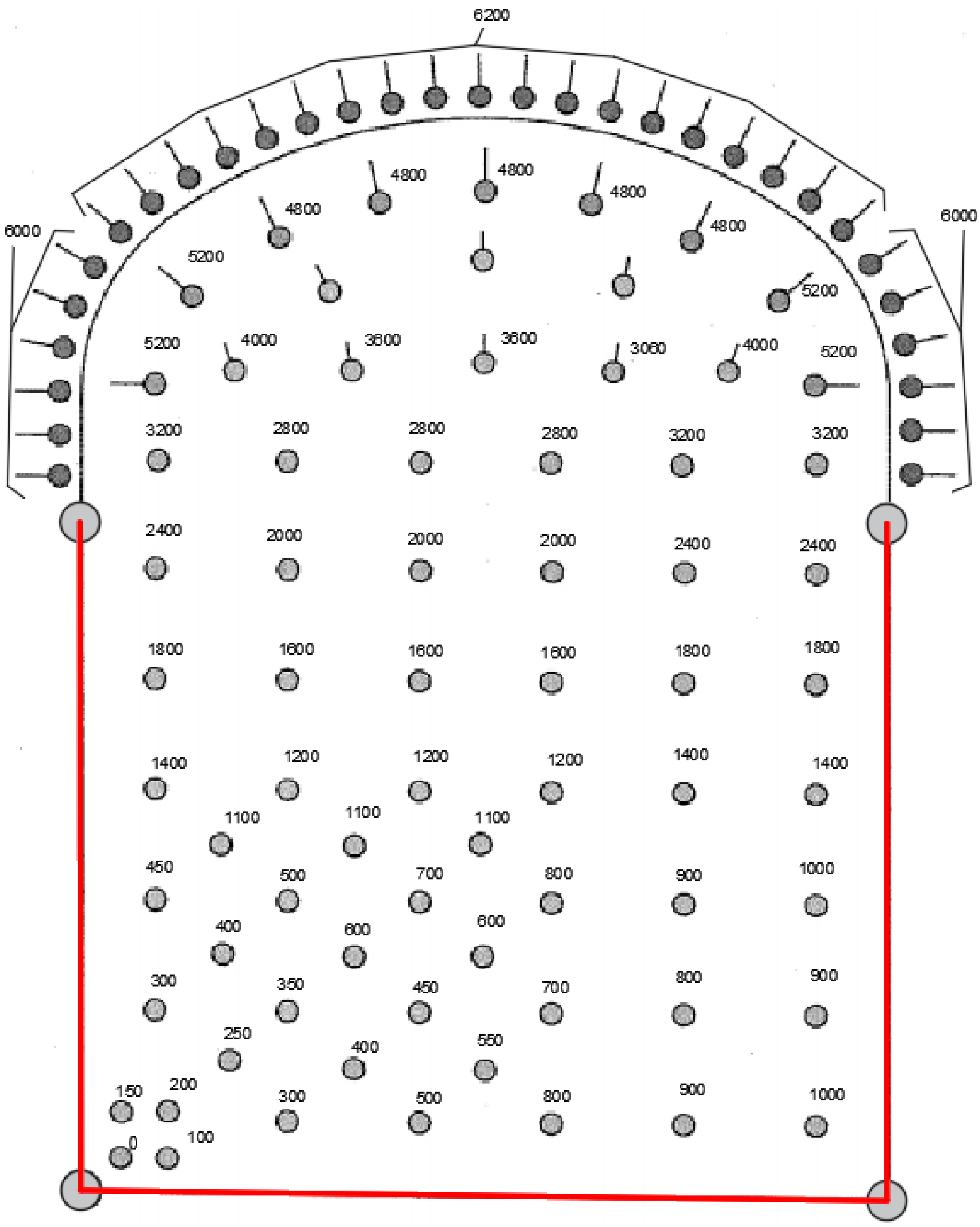

Figure 28. Drilling and charging plan that was used in Krångede. The red line illustrates the wire sawn floor and sidewalls.

As the bottom part and side walls were already cut by wire saw, there was no need for contour holes of the floor and side walls when drilling the tunnel face. As the number of drill holes could be reduced in the form of cut hole and contour holes, the amount of drill meters was lower than in normal tunnelling. Thus, the time consumed for drilling the round would be shorter. However, it should be noted that the blasting was carried out in shorter rounds than normal, so this prolonged the overall schedule.

A great benefit observed in Krångede is that there will not be over- or underbreaks in the tunnel floor or side walls as these will be cut by wire sawing, which gives an end result of smooth surfaces without significant fractures. Thus, there has not been any need for second blasting in order to repair the tunnel circumference. Figure 29 shows the tunnel excavated by a combination of wire saw cutting and the D&B method in Krångede.

Figure 29. Part of the new access tunnel in Krångede.

6.4 Rock reinforcement

As the end result of wire saw cutting is a smooth and uniform surface (as shown in Figures 29 and 30), temporary reinforcement for the wire cut surfaces does not need to be that much. In Krångede, rock bolts were used for the wire cut surfaces during the tunnelling just in the case the rock quality was very poor. Otherwise, the final reinforcement, including shotcrete and rock bolts, could be performed for the whole tunnel length at once. The roof contour that was excavated by the D&B method, was reinforced with a 50 mm thick layer of shotcrete and rock bolts in a pattern of 1 m x 1 m. After all the rounds have been blasted and the necessary rock reinforcement executed, the next cycle of wire saw cutting can begin.

Figure 30 also shows the shape of the cutting as described in Paragraph 4.4.1 based on the theory behind the cutting forces. More cutting has taken place at the lower part of the side wall as the cutting pressure increases along the cutting direction. For this reason, the shape is not completely symmetrical.

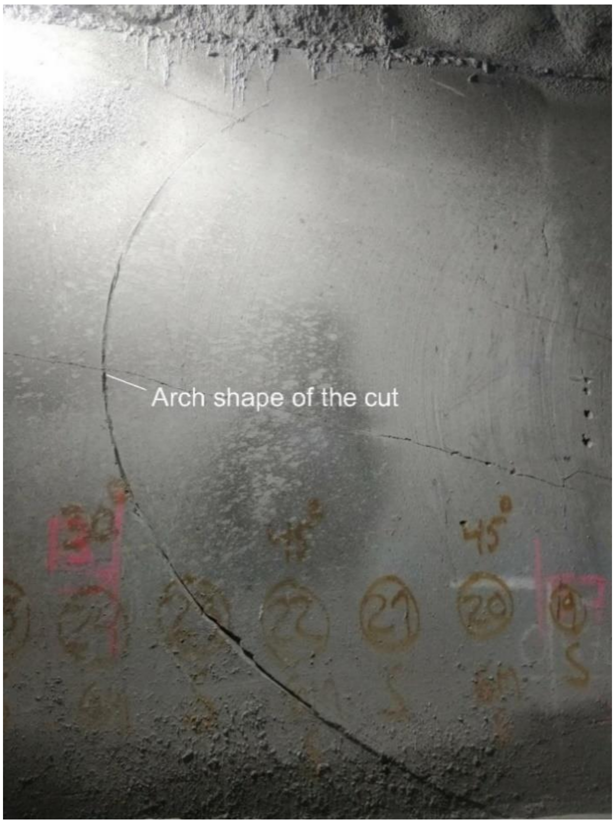

Figure 30. Tunnel wall cut by wire saw in Krångede.

6.5 Common problems and considerations faced in Krångede

1. Wire gets stuck in the slot during cutting.
    - Cutting cannot be continued for this section once the wire gets stuck. The section must then be excavated by drilling and blasting to get the wire out before the cutting can continue. This obviously causes delays in the schedule.
    - This has happened few times in Krångede. Common to all cases has been that the rock conditions have been poorer (rock fractures, joints, etc.).
2. Steel connector that connects the wire ends gets broken during cutting.
    - This has happened a few times in Krångede.
    - As the connector gets broken, the wire will be loosened from the guide pulleys. To reposition the wire, the rods must be taken out from the corner holes. This is obviously a time-consuming job.
    - In order to prevent this happening, the steel connectors need to be changed regularly. The change interval is based on how fast the connectors are wearing. According to operators, a suitable time interval for changing the connectors in the rock conditions of Krångede is every second hour. This is based on experience. According to the operators, a suitable time interval in some other rock conditions has been a few hours. The time necessary for carrying out this job is approximately 10 minutes, so there is a long pause in the cutting work every other hour.
3. According to operational knowledge, it is recommended to use wires that have the same level of wear when connecting these together. If some parts of a wire are more worn than others, cutting will not be uniform.
4. Bearing damage and the failure of guide pulleys have been quite common during this project.
    - If the bearing gets broken from the end of the rod, it is problematic as the rod must be removed from the corner hole in order to change the bearing/new guide pulley.

- Flushing is an important factor affecting the durability of the bearing and guide pulley as it removes the abrasive cuttings and cleans the guide pulley and bearing on it.

5. The sawing machine itself has been very reliable and safe to operate. According to experiences in Krångede, there have not been any problems or breakdowns with the machine. In site manager Pyykkönen's words, "As long as there is electricity, the machine will work."
6. If the rock quality is poor, there can be problems when installing the rods into the corner holes.
    - The hole may become blocked with rock pieces, which complicates the installation work. In this case, the hole needs to be cleaned first. To do that, a high-pressure water jetting truck may be needed if the blocked hole is deep, and cleaning is not successful otherwise.
7. Overall, poor rock quality complicates wire saw cutting. As already described, the wire can get stuck more easily and also the installation of the rods for the blind-cut can be difficult if the rock is fracturing a lot.

7 CONCLUSIONS

Based on the literature review and the visit to Krångede, wire saw cutting used together with the D&B method can be an alternative method for excavating a tunnel. According to the studies of Lee et al. (2016) and Song et al. (2014), vibration reduction when using pre-cut discontinuity surrounding blasting can be up to 50–57%. However, according to Christiansson et al. (2014), the vibration reduction was 20% when using a wire sawn tunnel perimeter. For this reason, further research is needed in order to determine the accurate effect in vibration reduction. As the average cutting rate of the blind-cut technique is approximately 2–5 m^2/h, it is recommended to use wire saw cutting in special cases only. Such a cases exist:

- if vibration limits are restricted,
- if the excavation needs to be carried out with the smallest excavation damaged zone (EDZ) as possible,
- if a smooth excavation surface is desired,
- if excavating precise geometrical dimensions,
- if excavating in an urban area close to structures and buildings or in an environment close to traffic,
- if excavating in a place where the working space is small and restricted and there is no space for large machines,
- if excavating in an area with decibel limits since wire saw cutting is a moderately quiet method (around 70 dB according to Salonen (2016)), and
- if other environmental restrictions do not allow the traditional D&B method, the combination of wire saw cutting and D&B may be possible.

Based on the Gustafsson (2010) study, the cost for a tunnel excavated by the combination of wire saw cutting and the D&B method is approximately double that compared to a tunnel excavated by the D&B method alone. On the basis of information obtained from the site visit, the cost of wire saw cutting per square metre is approximately EUR 200–400 when using the blind-cut technique. If this also includes the installation and disassembly of equipment, drilling and reaming of blind-cut holes, as well as other operating expenses, the cost is approximately EUR 350–700 per square metre. In order to make wire saw cutting more practical and competitive compared to the traditional D&B method, the cost for it should be lower. This can be achieved by improving the effectiveness and productivity of the method.

As the wire is exposed to a tension force during the cutting, it will wear and, at a certain point, cause a wire break. For this reason, the condition of the wire must be observed during the cutting process in order to prevent such breaks. Moreover, the steel sleeve that connects the wire ends must be changed regularly in order to avoid the failure of that part. From the operational parameters, wire and bead wear are mostly affected by wire speed and feed rate. A broken wire is extremely dangerous for anyone nearby and can possibly get stuck in the cutting slot, which can cause difficulties for the continuation of the operation. Other equipment problems are mainly related to the guide pulleys. If the bearing of the guide pulley breaks, it must be replaced. This becomes problematic if the bearing breaks from the bottom of the guide hole, as the rod must be removed in order to change the bearing. Such breaks can be prevented by sufficient flushing, which cleans the bearing of cuttings. Otherwise, the equipment for wire saw cutting seems to be relatively reliable, so unexpected expenses for spare parts are not common.

Poor rock quality may complicate the execution of wire saw cutting. A wire will get stuck more easily when the rock fractures and also the installation of the rods in the guide holes can be difficult. This can be predicted by mapping the rock mass properly. In such cases, pregrouting of the rock mass can prove beneficial as it prevents the fracturing of rock.

8 RECOMMENDATIONS

Wire saw cutting still remains a relatively under-researched field in relation to tunnel excavations, which means there is still multiple issues that could be studied in future. It seems that there is especially a lack of practical examples where wire saw cutting has been used in a real tunnel site, as there were just a few literature reviews of such cases. Otherwise, the theoretical background regarding wire saw cutting and the cutting mechanism is a relatively well-researched field as the method has been used in the dimension stone industry for decades. This knowledge can be used when studying the cutting mechanism and theory behind it but, for example, operational knowledge, execution of the method, costs, cutting forces, etc., cannot be compared as the blind-cut technique and tunnel environment are completely different compared to those in the dimension stone industry. Future research topics could include the following:

- Cutting rate in the blind-cut technique and its improvement. Things to consider in terms of the cutting rate could be the effect of wire speed, the effect of pullback force, the effect of flushing fluid, the effect of cutting dimensions and the effects of rock characteristics. In order to perform this kind of study, there should be a worksite where accurate measurements and comparisons of the cutting rate with different parameter changes could be done.
- Costs and schedule for executing wire saw cutting together with the D&B method compared to the costs and schedule for the traditional D&B alone in tunnelling. To carry out extensive research, there should be detailed data on:
    1. The costs and execution time of wire saw cutting together with the D&B method.
    2. Data on the D&B method from a tunnel site with vibration restrictions.
    3. Data on the D&B method without any vibration restrictions.

  By comparing these situations, the difference in costs and schedule between the options could be studied. Rock reinforcement could be also taken into account, as wire saw cutting can reduce the amount of reinforcement required, which obviously decreases the schedule and costs in this working phase. In this way, the results would be reliable and comparable.

- Blasting vibrations with and without pre-cut discontinuity made by wire saw cutting. Based on the existing research, it is not possible to reach convincing conclusions about the level of vibration reduction when wire saw cutting is used together with the D&B method. In this kind of research, the effects on vibration reduction could be studied in the following manner:
    1. The level of blasting vibrations when the traditional D&B method is used.
    2. The level of blasting vibrations when using the D&B method together with the wire sawn tunnel perimeter.
    3. The level of blasting vibrations when using the D&B method together with only a partially cut tunnel perimeter; for example, the floor and side walls.
    4. The level of blasting vibrations when using the D&B method together with wire cut surface only around or above the cut holes in blasting. If this method were effective enough in vibration reduction, it would save a considerable amount of time as the area for the wire cut surface would be reduced significantly.

9 SUMMARY

The purpose of this thesis was to study wire saw cutting especially in the field of underground infrastructure projects. The method has been widely used in the dimension stone industry already for decades, but it was only in 2010 when the use was considered for tunnelling. The technique used for this purpose is called the blind-cut technique.

This study consisted of a presentation of the different working phases in tunnelling in order to give insight into which stage wire saw cutting is used and how it affects the execution of tunnelling. Also, the use of wire saw cutting for shafts and different kinds of cuts was presented. A broad theoretical literature review of wire saw cutting was conducted on the basis of previous research in which the cutting mechanism, cutting forces, cutting effectiveness, specific energy of cutting, power consumption, bead wear, flushing and other operational parameters were studied, especially from the point of view of the blind-cut technique. The aim was to carry out an extensive review regarding the theory and execution of wire saw cutting in order to better understand the topic. There is still relatively little research and few practical examples available on wire saw cutting in tunnelling. Due to the poor availability of valid and reliable data concerning the blind-cut technique, it was difficult to draw convincing comparisons and conclusions.

To better understand the concept of blasting vibrations and the effect of pre-cut discontinuity made by wire saw cutting on vibration reduction, a theoretical literature review related to the propagation of blasting waves was conducted. The effectiveness of the pre-cut discontinuity on vibration reduction is based on evidence that the blasting area is separated from the surrounding rock mass. This kind of slot can effectively reduce the propagation of seismic waves into the surroundings. According to the literature review, vibration reduction can be up to 57% with pre-cut discontinuity; however, further research is needed in order to determine a more accurate estimate.

In addition to the theoretical study, the study included a visit to the site in Krångede, Central Sweden, where wire saw cutting together with the D&B method are being used to excavate a new access tunnel at the hydropower plant. On the basis of the visit, a practical review of the execution of the method and common problems faced during the production was presented. The visit enabled a deeper understanding of the subject and taught many things from the practical aspect that were studied already on the theoretical level.

Overall, it can be concluded that wire saw cutting together with the D&B method can be an effective excavation method, but only in special cases. The reason for this is the extended execution schedule and obviously increasing costs. Situations when the method could be useful are mostly related to environmental restrictions such as vibration levels and noise levels. Other benefits include the possibility of excavating precise geometrical dimensions, a smooth excavation surface and overall environmental friendliness, as wire saw cutting does not cause emissions or toxic gases as is the case with explosives. In order to make more accurate comparisons, such as those related to the schedule and costs, further research is needed in the future.

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